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PSYCHOPHYSICAL BASES FOR THE SENSORY ASSESSMENT OF RATIONS

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Development of acceptable and nutritious rations requires the judicious use of sensory evaluation techniques. An appreciation of the philosophical, historical and mathematical basis of these methods is necessary for their successful application. This report traces the origins of the methods and delineates the methods that are available for the sensory analysis of foods, rations and beverages.

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PREFACE

The development of acceptable and nutritious rations requires the use of sensory evaluation techniques. These techniques have evolved, to a large degree, from the discipline of psychology (psychophysics). Appreciation and understanding of the historical, philosophical and mathematical bases for these methods are essential for their successful application. This report traces these origins, and delineates the methods that we currently have to conduct the sensory evaluation of foods and rations.

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PSYCHOPHYSICAL BASES FOR THE SENSORY ASSESSMENT OF RATIONS

I. INTRODUCTION

Food quality has been defined as "the combination of attributes or characteristics of a product that have significance in determining the degree of acceptability of the product to a user."[1] These attributes or characteristics include the nutritional value, microbiological safety, convenience, stability, cost and the sensory characteristics of the product - its appearance, odor, flavor, texture, etc.

Due to the variety of factors contributing to food quality, it is not surprising that their relative importance is product-dependent. For some foods, such as dairy products and baked goods, stability may be an important characteristic. For other foods such as frozen entrees and beverage mixes, convenience may be more important. However, an argument can be made that, for the average consumer, the factors most closely associated with the concept of food quality are those related to the sensory characteristics of the food. The reasons for this close association are varied, but one reason is that the sensory characteristics of a food are more salient than are its other characteristics. Whether foods or beverages are purchased at a restaurant, bought in a supermarket, or eaten in an institutional setting, their sensory characteristics can be readily appreciated by consumers and can be used as a basis for assessing the quality of the product. In contrast, nutritional, convenience and shelf-life properties of the food cannot be directly assessed by consumers for food purchased in restaurants or cafeterias and can only be assessed through information provided by the producer for foods purchased in the supermarket. Microbiological safety, while important to all consumers, cannot readily be evaluated in purchased foods, and cost, while an important factor to many consumers, may not be of concern to some. The hedonic (like/dislike) dimension of food also contributes to the importance of sensory characteristics in the assessment of quality. The pleasurable sensory effects produced by eating a piece of rich cheesecake after dinner or by drinking a glass of cold beer on a hot day may override nutritional, economic, health and other considerations of the consumer in forming an opinion about the quality of the product.

The fundamental importance of food quality to humans, as well as to other living organisms, is reflected in the number of sensory systems involved in locating, evaluating, selecting and preparing a potential food for consumption. Such food sources are subjected to complex, multi-sensory information processing. For most mammals, including humans, this process involves detection of food by the sense of sight or smell. This is usually followed by further sniffing, and then by visual and tactual inspection and

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[1]U.S. Department of Agriculture Marketing Workshop Report, 1951. In W. A. Gould, Food Quality Assurance. Westport, CT: AVI Publishing, 1977.

placement of the food in the mouth, where the taste and thermal properties of the stimulus are evaluated. During subsequent chewing, the textural properties of the food are assessed through the tactile and kinesthetic senses. In this final stage of pre-consummatory behavior, the auditory system also becomes involved as the sound of the food being chewed provides further sensory information about its textural properties. The integration of this immediate sensory information with past experience (memories) produces a judgment of the quality and/or acceptability of the food and a decision about whether or not it should be consumed.

A.   Subjective vs. Objective Approaches to Sensory Evaluation

A major task of many food processors is to define and measure the sensory characteristics of their products for such purposes as product development, optimization, specification, quality assurance and marketing. In general, there are two approaches that can be used. These approaches, as applied to the flavor and texture of food, are shown in Figure 1. The first approach, shown in the top two sections, is termed "subjective" and uses humans as the measuring instruments. Although this approach is the most direct and, in many cases, the most sensitive, it is costly and time-consuming. As a result, an alternative approach is frequently used. This second approach, shown in the bottom two sections of Figure 1, is termed "objective" and uses mechanical instruments to measure the physicochemical properties of a food that are presumed to be associated with its sensory properties. Although the subjective approach is sometimes criticized for its lack of reliability (due to judgmental errors and individual differences in perception), the validity and usefulness of the objective (instrumental) approach depends upon the identification of meaningful correlations with sensory measures (graph in upper right section of Figure 1). The present discussion will focus on the technologies involved in the subjective approach.

B.   Historical Perspective

Due to the convenience and cost efficiency of instrumental approaches to quality control, the study of subjective/objective correlations has received considerable attention in recent years. However, the origins of this study are centuries old, dating back to the 13th and 14th centuries, when German alemakers discovered that the sensory quality of their ale was related to the degree to which the ale adhered to the bottom of their leather britches after the ale was spilled on wooden benches.[2] From such early observations, the conceptual framework for studying subjective/objective correlations evolved, attaining status as an independent field of inquiry in mid-19th century Germany, with the development of the branch of experimental psychology known as psychophysics.

[2]H.S. Corran. A History of Brewing. London: Davis and Charles, 1975, 40.
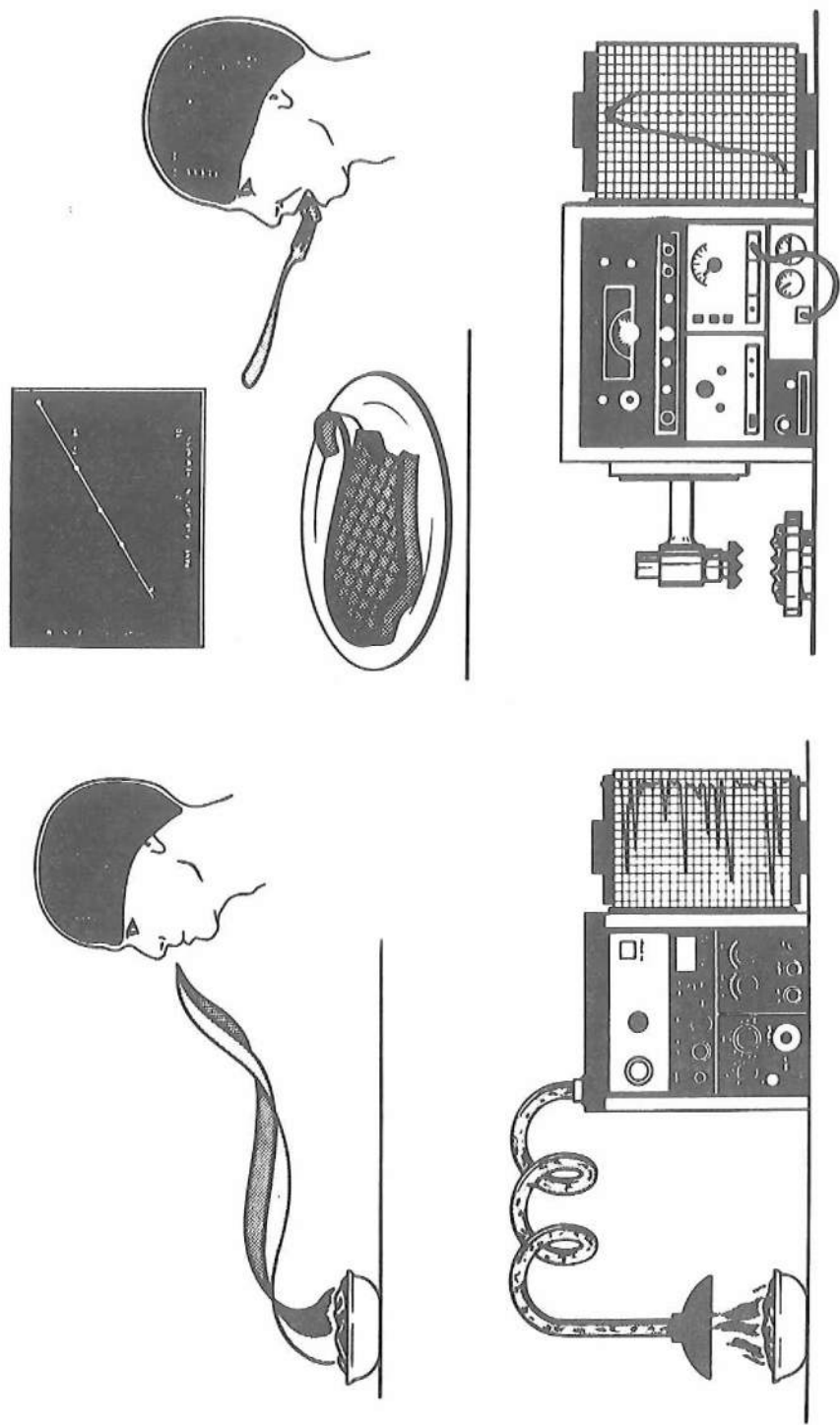
Figure 1. Schematic representation of subjective (top) and objective (bottom) approaches to quality control and evaluation of the food senses of flavor (left) and texture (right). The plot of objective versus subjective measures (upper right) is the key to identify-ing objective measures that will predict sensory responses.

The field of psychophysics was founded by the German physicist, philosopher and psychologist, Gustav Fechner. Fechner defined psychophysics as "the exact science of the functionally dependent relations between body and soul or more generally of the material and the mental, of the physical and psychological worlds."[3] Operationalizing Fechner's definition, the goal of psychophysics is the determination of the mathematical relationships between sensations and the physical or chemical stimuli that elicit them. This relationship can be stated in the following form:

$$\Psi = f(\phi) \tag{1}$$

where Ψ is a quantifiable aspect of sensation and ϕ is a physical measure of the stimulus that produced that sensation.

Within the context of today's problems of quality assessment in the food industry, the Ψ of Equation 1 might be the perceived intensity of aroma in a cup of brewed coffee, while ϕ might be the peak magnitude in a gas chromatograph of the product; or Ψ might be the perceived hardness of a biscuit, while ϕ is the yield shear stress as measured on an Instron Universal Testing Instrument. We will return to a more detailed discussion of this basic psychophysical equation in later sections.

With the founding of the science of psychophysics, a variety of investigations were undertaken in an attempt to relate the perceived attributes of stimuli to their physical composition. Much of this work was predicated on existing knowledge about the number and nature of attributes capable of appreciation by the human senses, and the resulting focus on sensory/perceptual problems resulted in a proliferation of information on the qualitative and quantitative aspects of human sensory/perceptual experience. This body of information now forms the basis for the current study of the sensory properties of food.

The procedures used to identify meaningful correlations between sensory and objective measures of food can be divided into several stages. These include:

1. Identifying subjective (sensory) attributes of the product that are important to its characterization;

2. Measuring the extent or degree to which the product possesses each of these attributes;

3. Identifying objective (instrumental) measures that are believed to be related to the sensory attributes of the product;

4. Making the objective measurements;

5. Determining the mathematical relationships existing between the subjective and objective measures.

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[3]G.T. Fechner. Elements der Psychophysik. Leipzig: Breitkopf und Harterl, 1860. English translation by H.E. Adler. New York: Holt, Rinehart and Winston, 1966.

Of these five stages, stages 1, 2 and 5 involve sensory methodology and the relationships between sensory measures and instrumental measures. This report will be divided into several sections, each covering topics related to one of these three procedural stages.

Following the introduction, Sections II and III focus on stage 1 and the identification of the qualitative dimensions of sensory experience important for describing food. The first section will review basic research and theories concerning qualitative attributes within the food senses, with emphasis on the nature and number of basic sensory attributes and on the physical/chemical stimuli that are known to elicit them. The second section will review applied methods of descriptive food analysis.

The next two sections will focus on stage 2, which involves the quantitative dimension of sensory experience. Here we will review current knowledge concerning the measurement of sensations. In the first of these sections, the reader will be provided with an understanding of the important theoretical issues in sensory scaling. In the second section, the reader will be provided with a review of scaling methods and their application to food problems. Other psychophysical problems, such as threshold determinations and difference measurements, will be discussed only as they relate to the problems of scaling. For the reader who wishes to review these other problem areas, a number of excellent texts are available.[4-6]

The last section will focus on stage 5 and the methods for determining the mathematical relationships between sensory and instrumental measures of food.

II. THE QUALITATIVE DESCRIPTION OF SENSORY DATA: BASIC RESEARCH AND THEORY

A. Modality vs. Quality

At the outset it is important to distinguish between two terms: modality and quality. Modality refers to individual sensory systems. These were identified by Aristotle as vision (sight), audition (hearing), somesthesis (touch), gustation (taste) and olfaction (smell). However, these five senses comprise only what Sherrington[7] termed the

[4]M.A. Amerine, R.M. Pangborn, and E.B. Roessler. Principles of Sensory Evaluation of Foods. New York: Academic Press, 1965.

[5]R.S. Woodworth and H. Schlosberg. Experimental Psychology, 3rd ed. J.W. Kling and L.A. Riggs (eds). New York: Holt, 1971.

[6]S.S. Stevens. Handbook of Experimental Psychology. New York: Wiley, 1951.

[7]C.S. Sherrington. The Integrative Action of the Nervous System. London: Constable, 1906.

exteroceptors – those senses whose receptors are located on the periphery of
the body. In addition to these, there are **proprioceptors**, sensory systems in
which the receptors are located inside the body. These include the vestibular
sense (balance), the kinesthetic sense (body and limb position) and the sense
of deep pressure. Lastly, there are interoceptors, which are located within
the core of the body, (i.e. in the gastrointestinal tract) which provide
information about stomach distention, intestinal motility, etc.

Five of the nine sensory modalities listed above are directly involved in
the perception of food. These are **vision, taste, smell, somesthesis** and
kinesthesis. Audition is often indirectly involved as a result of vibrations
emitted through the air or through cranial bones during mastication. In
addition, the interoceptors of the gastrointestinal system are involved in
pre-and post-ingestional perception of food, e.g., hunger and/or satiety.

Within each sensory modality, we can experience a wide variety of
qualitatively different sensations. For example, within the visual modality,
one can distinguish among the sensations of blue, yellow, red, green, etc.,
and within the taste modality one can distinguish among the sweet, salty, sour
and bitter tastes. These different sensations within each modality are called
qualities, and can be thought of as the fundamental sensory experiences
contributing to complex perception. Therefore, in order to describe
adequately the sensory characteristics of a food, it is necessary to know the
basic qualities that can be mediated by the food-allied senses, as well as the
underlying mechanisms of sensory functioning.

B.   Taste

Taste is the subjective experience (sensation) resulting from stimulation
of chemosensory receptors (taste buds) located on the tongue, palate, pharynx,
larynx, and certain other areas of the oral cavity by chemicals or chemical
components of food in solution with saliva. Aristotle believed that there
were two primary gustatory qualities – **sweet** and **bitter**. Other qualities,
described as saline, acid, pungent, astringent and harsh, fell between these
two. Throughout the early and middle ages, the names and number of taste
qualities changed repeatedly, and it was not until 1864 that Fick[8] first
proposed the view of four primary taste qualities – **salty, sweet, sour** and
bitter. Some 60 years later, Henning[9] schematicized these four basic tastes
as corners of a tetrahedron (Figure 2). In his "taste tetrahedron," taste
sensations composed of three primaries were located on the surfaces, and
sensations composed of all four primaries were located within the interior.

[8]A. Fick. Anatomie des geschmacksorganes. In Lehrbuch der Anatomie und
Physiologie der Sinnesorgane. Lahr: M. Schauenberg und Company, 1864.

[9]H. von Henning. Psychologiche studien an geschmackssinn. In Handbuch der
Biologischen Arbeitsmethoden. Berlin: Abderhalden, Urban & Schwarzenberg,
1927.

While most early investigators followed the Aristotelean lead in assuming the existence of taste primaries, Frings,[10] in 1948, proposed that the four "basic" taste qualities were only "points of familiarity along a continuous taste spectrum." More recently, Erickson[11-13] has also argued against the concept of taste primaries, basing his position on electrophysiological data that show the responses of taste neurons to vary more widely than would be expected if each neuron responded best to only one or a few taste primaries. The evidence in favor of the existence of taste primaries has recently been summarized by McBurney[14-15] and until a better schema is proposed, most researchers still adhere to the notion of four basic taste qualities – salty, sweet, sour and bitter.
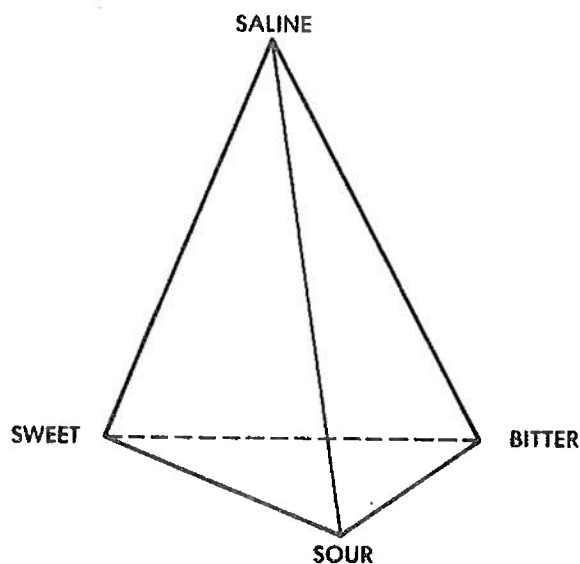
Figure 2. Henning's taste tetrahedron.

[10]H. Frings. A contribution to the comparative physiology of contact chemoreception. J. Comp. Physio. Psychol., 41, 25 (1948).

[11]R.P. Erickson. Neural coding of taste. In The Chemical Senses and Nutrition. M. Kare and O. Maller (eds). Baltimore: Johns Hopkins Press, 1967.

[12]R.P. Erickson. The role of "primaries" in taste research. In Olfaction and Taste VI. J. LeMagnen and P. Macleod (eds). Washington: Information Retrieval, 1977.

[13]R.P. Erickson and E. Covey. On the singularity of taste sensations: What is a taste primary? Physiol. & Behav., 25, 527 (1980).

[14]D.H. McBurney. Are there primary tastes for man? Chem. Senses & Flavor, 1, 17 (1974).

[15]D.H. McBurney and J.F. Gent. On the nature of taste qualities. Psych. Bull., 36, 151 (1979).

Although many different foods may taste sweet, sour, etc., it is generally assumed that each of the four taste qualities is elicited by a single chemical stimulus. Perhaps the best and earliest known of these is the chemical stimulus for the sour quality - the hydrogen ion (H+). As the defining characteristic of acids, the hydrogen ion is assumed to be the stimulus that is responsible for the sourness of such acid-containing foods as citrus fruits, vinegar and sour milk. Although several models of the mechanism of sour receptor stimulation have been proposed and reviewed in the literature,[16-19] each must contend with the fact that not all acids are sour. Some amino acids are sweet and others are bitter. Also, the threshold number of hydrogen ions necessary for perception of a sour taste is smaller for weak acids than for strong acids. These facts suggest that the anion and/or any undissociated acid may modify the taste of these compounds. In addition, the lipophilicity of the compound may play a role by affecting access of the compound to the receptor.[20]

The salty quality, like the sour quality, is the result of ionic stimulation. However, the importance of salt taste to the appreciation of food has gained wide attention in recent years due to the significant use of NaCl to flavor foods and the resultant health risks associated with this

[16]L.M. Beidler. Anion influences on taste receptor response. In Olfaction and Taste II. T. Hayashi (ed). New York: Pergamon Press, 1967, 509.

[17]L.M. Beidler. Taste receptor stimulation with salts and acids. In Handbook of Sensory Physiology. IV. Chemical Senses. 2. Taste. L.M. Beidler (ed). New York: Springer-Verlag, 1971, 200.

[18]G.M. Makhlouf and A.L. Blum. Kinetics of the taste response to chemical stimulation: A theory of acid taste in man. Gastroenterol. 63, 67 (1972).

[19]S. Price and J.A. Desimone. Models of taste receptor cell stimulation. Chem. Senses & Flavor, 2, 427 (1977).

[20]R.J. Gardner. Lipid solubility and the sourness of acids: Implications for models of the acid taste receptor. Chem. Senses & Flavor, 5, 185 (1980).

[21]L.M. Beidler. Properties of chemoreceptors of tongue of rat. J. Neurophysiol., 16, 595 (1953).

[22]L.M. Beidler. A theory of taste stimulation. J. Gen. Physiol., 38, 133 (1954).

[23]L.M. Beidler. Physiological properties of mammalian taste receptors. In Ciba Foundation Symposium on Taste and Smell in Vertebrates. G.E.W. Wolstenholme and J. Knight (eds). Churchill, London, 51, 1970.

[24]L.M. Beidler. Biophysics and chemistry of taste. In Handbook of Perception, Vol. VIA: Tasting and Smelling. E.C. Carterette and M.P. Friedman (eds). New York: Academic Press, 1978, 21.

practice. Although electrophysiological evidence from animals[21-24] has shown that the magnitude of taste responses to salts is primarily due to the cation, with the anion playing a possible inhibitory role, early human psychophysical data[25-28] suggested that the chloride anion was the adequate stimulus for the salty taste. More recent data[29-31] have established that the cation, especially Na+, is responsible for eliciting the salty taste quality in humans and that the anions play an inhibitory role. Of additional importance to understanding the mechanism underlying the salty taste is the fact that many inorganic salts in solution taste different depending upon molecular concentration. At low concentration, many salts (including sodium chloride) taste sweet.[30-36] With increasing concentration the taste of these salts

[25]L. Kahlenberg. The action of solutions on the sense of taste. University of Wisconsin Bulletin, Science Series, 2, 1 (1898-1901).

[26]R. Hober and F. Kiesow. Ueber den geschmack von salzen und laugen. Zeitschrift fur Physikalische Chemie, 27, 601 (1898).

[27]H. Kionka and F. Stratz. Setzt der geschmack eines salzes sich zusammen aus dem geschmack der einzelnen ionen oder schmeckt man jedes salz als gesantmolekul? Arch. Exp. Path. Pharmakol. 95, 241 (1922).

[28]E. Dzendolet and H.L. Meiselman. Cation and anion contributions to gustatory quality of simple salts. Percept. & Psychophys., 2, 601 (1967).

[29]L.M. Bartoshuk, B. Rifkin and M. Speers. Taste of salts. In Olfaction and Taste VII. H. Van der Starve (ed). London: IRL Press, 1980.

[30]C. Murphy, A.V. Cardello, and J.G. Brand. Tastes of fifteen halide salts following water and NaCl: Anion and cation effects. Physiol. & Behav., 26, 1083 (1981).

[31]L.M. Bartoshuk. Sensory analysis of the taste of NaCl. In Biological and Behavioral Aspects of Salt Intake. M.R. Kare, M.J. Fregley, and R.A. Bernard (eds). New York: Academic Press, 1980, 83.

[32]Y. Renqvist. Ueber den geschmack. Skand. Arch. Physiol., 38, 97 (1919).

[33]E. Dzendolet and H. Meiselman. Gustatory quality changes as a function of solution concentration. Percept. & Psychophys., 2, 29 (1967).

[34]A.V. Cardello and C. Murphy. Magnitude estimates of gustatory quality changes as a function of solution concentration of simple salts. Chem. Senses & Flavor, 2, 327 (1977).

[35]L. Bartoshuk, C. Murphy, and C. Cleveland. Sweet taste of dilute NaCl: Psychophysical evidence for a sweet stimulus. Physiol. & Behav., 21, 609 (1978).

[36]A. Cardello. Taste quality changes as a function of salt concentration in single human taste papillae. Chem. Senses & Flavor, 4, 1 (1979).

may be salty, sour and/or bitter. At first glance, these taste quality changes pose difficulties for the identification of a single chemical structure responsible for the salty quality. However, research has shown that these taste quality changes can be explained by physicochemical changes (e.g., localized hydrolysis) that occur in these salts as a function of concentration.[35-38] This proposition, that the chemical structures existing in salt solutions actually differ at different concentrations, offers an adequate explanation of the quality changes, while preserving the notion of specific physicochemical stimuli for each quality.

In contrast to the sour and salty qualities, where attempts to define adequate stimuli have met with relative success, the sweet and bitter qualities still present a complex picture. The sweet quality is elicited by a variety of food-related organic compounds and by some inorganic compounds, such as lead and beryllium salts and halide salts at low concentrations. The most common sweeteners are, of course, the sugars, which vary considerably in sweetness. Based on equimolar solutions, it has been suggested[39,40] that the order of sweetness for common food sugars is sucrose⟩fructose⟩maltose⟩ glucose⟩lactose. However, the relative sweetnesses of sugars have been shown to vary with concentration,[41-45] with the medium (or food) in which they are

[37]J.T. Kuznicki and N. Ashbaugh. Taste quality differences within the sweet and salty taste categories. Sensory Processes, 3, 157 (1979).

[38]E. Dzendolet. A structure common to sweet-evoking compounds. Percept. & Psychophys., 3, 65 (1968).

[39]A.T. Cameron. The taste sense and the relative sweetness of sugars and other sweet substances. Scientific Report Series No. 9. New York: Sugar Research Foundation, 1947.

[40]H.R. Moskowitz. Ratio scales of sugar sweetness. Percept. & Psychophys., 7, 315 (1970).

[41]A.T. Cameron. The relative sweetness of sucrose, glucose, and fructose. Transact. Royal Soc. of Canada, 37, 11 (1943).

[42]A. Dahlberg and E. Penczek. The relative sweetness of sugars, as affected by concentration. N.Y. Agr. Exp. Station Bull., 258, 1 (1941).

[43]Y. Tsuzuki and J. Yamazaki. Sweetness of fructose and some other sugars, especially its variation with temperature. J. Biochem. Ztg., 323, 525 (1953).

[44]L. Hyvonen, R. Kurkela, P. Koivisteinen, and P. Merimaa. Effects of temperature and concentration on the relative sweetness of fructose, glucose, and xylitol. Lebensm. Wiss. Technol., 10, 316 (1977).

[45]A. Cardello, D. Hunt, and B. Mann. Relative sweetness of fructose and sucrose in model solution, lemon beverages and white cake. J. Food Sci., 44, 748 (1979).

presented[45-51] and with the temperature of the medium,[43,44,52] thereby making generalizations across food classes difficult.

Several early theories were proposed for relating the chemical structure of compounds to their sweet taste;[53-55] however, none of these were able to account adequately for the wide variety of sweet-tasting compounds. Currently only two major theories do so. They are the hydrogen-bond theory[56,57] and the proton-acceptor theory[38] of sweet taste. Briefly, the hydrogen-bond theory[56,57] proposes that the common characteristic of all sweet-tasting substances is the presence of an AH-B hydrogen bond complex, where AH+ is a hydrogen ion bonded to an electronegative atom, such as oxygen or nitrogen, and in close proximity to this group there coexists an electronegative atom

[46]F. Fabian and H. Blum. Relative taste potency of some basic food constituents and their competitive and compensatory action. Food Res., 8, 179 (1943).

[47]R.M. Pangborn. Taste interrelationships. Food Res., 25, 245 (1960).

[48]R.M. Pangborn. Taste interrelationships. 2: Suprathreshold solutions of sucrose and citric acid. J. Food Sci., 26, 648 (1961).

[49]R.M. Pangborn. Relative taste intensities of selected sugars and organic acids. J. Food Sci., 28, 726 (1963).

[50]H. Stone and S. Oliver. Measurement of the relative sweetness of selected sweeteners and sweetener mixtures. J. Food Sci., 34, 215 (1969).

[51]H. Moskowitz. Intensity scales for pure tastes and for taste mixtures. Percept. & Psychophys., 9, 51 (1971).

[52]H. Stone, S. Oliver, and J. Kloehn. Temperature and pH effects on the relative sweetness of suprathreshold mixtures of dextrose fructose. Percept. & Psychophys., 5, 257 (1969).

[53]G. Cohn. Die Organischen Geschmackstoffe. Berlin: Siemenroth, 1914.

[54]S. Kodama. Taste. J. Tokyo Chem. Soc., 41, 495 (1920).

[55]G. Beck. Sweetness and molecular volume. Wien. Chem. Ztg., 46, 18 (1943).

[56]R.S. Shallenberger and T.E. Acree. Molecular theory of sweet taste. Nature, 216, 480 (1967).

[57]R.S. Shallenberger and T.E. Acree. Chemical structure of compounds and their sweet and bitter tastes. In Handbook of Sensory Physiology. L. Beidler (ed). New York: Springer-Verlag, 1971.

(B), which permits the formation of a hydrogen bond. It has been proposed that sweet compounds have an AH-B distance of three Å. Although this is too great a distance for intermolecular hydrogen bonding to occur, it allows for hydrogen bond formation with the receptor surface. In contrast to the hydrogen bond theory, the proton-acceptor theory[38] proposes that the property common to sweet-evoking compounds is that they are proton-acceptors. Thus, the initial step in the mechanism of sweet stimulation is suggested to be the removal of protons from taste receptor sites by proton-accepting chemical structures present in foods.

While both theories account for much of the available data on the perception of sweet taste, designing experimental tests that will distinguish between the two theories is difficult. As one of the two theory proponents stated, "all the arguments in favor of the AH-B system as the saporous unit of a sweet-tasting compound can also be offered to support the thesis that the initial mechanism is one of proton exchange."[57] Further resolution of the problem will depend on progress currently being made in the biochemistry of taste receptor membranes.

The bitter taste quality, important for its ability to alert the organism to dangerous compounds in food, is even more difficult than the sweet quality to associate with a specific stimulus. While the most prominent class of bitter-tasting compounds is the alkaloids, e.g., quinine, caffeine and nicotine, many heavy halide salts and amino acids also taste bitter.[30,58] In addition, certain bitter-tasting compounds, such as phenylthiocarbamide, have been shown to be tasteless to certain individuals.[59,60] This phenomenon, believed to be due to a Mendelian recessive characteristic among nontasters, introduces genetic considerations into the understanding of taste perception and raises questions about the possible genetic basis for individual preferences for bitter foods.

Since many of the bitter-tasting organic substances have similar structures to sweet-tasting compounds (e.g., α-D-mannose is sweet, but β-D-mannose is bitter), attempts have been made to find a common stimulating

[58]H. Kionka and F. Stratz. Setzt der geschmack eines salzes sich zusammen aus dem geschmack der einzelnen Ionen odor schmeckt man jedes salz als gesamtmolekul. Arch. Exp. Path. Pharmakol., 95, 241 (1922).

[59]A.L. Fox. The relationship between chemical constitution and taste. Proc. Nat. Acad. Sci. USA, 18, 115 (1932).

[60]H. Kalmus. Genetics of taste. In L. Beidler (ed). Handbook of Sensory Physiology, IV: Chemical Senses, 2: Taste. New York: Springer-Verlag, 1971, 165.

mechanism. One suggestion [61-63] is that the physicochemical feature common to bitter-tasting compounds is also an AH-B system, with an AH-B distance of 1.5 Å being suggested for diterpenes.[61] In addition, the lipophilicity of the compound has been implicated in bitterness perception[64,65] as it relates to the ability of the compound to reach the receptor surface.

Although not having the status of "primary tastes," two other types of sensations are commonly associated with the sense of taste. These are "metallic" taste and "umami"[66,67] sensation. The former is elicited by certain metallic salts, e.g., silver nitrate; while the latter is elicited by certain L-amino acids, e.g., monosodium glutamate, and by certain 5'-ribonucleotides. Other sensations that are often associated with taste, e.g., "pungency" and "astringency," are really tactile in nature and will be covered in a later section.

C.   Smell

While taste is an important factor in the appreciation of food flavors, smell still plays a preeminent role in flavor perception. Smell refers to sensations resulting from stimulation of chemosensory receptors located in the olfactory epithelium of the nose by airborne chemical compounds. These chemicals may reach the epithelium directly through the nares, or, as is more often the case, rostronasally through the mouth when food is being consumed.

[61]T. Kubota and I. Kubo. Bitterness and chemical structure. Nature, 223, 97 (1969).

[62]P.A. Temussi, F. Lelj, and T. Tancredi. Three dimensional mapping of the sweet taste receptor site. J. Med. Chem., 21, 1154 (1978).

[63]T. Tancredi, F. Lelj, and P.A. Temussi. Three dimensional mapping of the bitter taste receptor site. Chem. Senses & Flavor, 4, 259 (1979).

[64]R.J. Gardner. Lipophilicity and bitter taste. J. Pharm. Pharmac., 30, 531 (1978).

[65]R.J. Gardner. Lipophilicity and the perception of bitterness. Chem. Senses & Flavor, 4, 275 (1979).

[66]J.C. Boudreau, J. Oravec, N.K. Hoang, and T.D. White. Taste and the taste of foods. In Food Taste Chemistry. J.C. Boudreau (ed). Washington, DC: American Chemical Society, 1979.

[67]S. Yamaguchi. The umami taste. In Food Taste Chemistry. J.C. Boudreau (ed). Washington, DC: American Chemical Society, 1979.

The sensory qualities of smell are numerous and still open to debate. Aristotle believed that the qualities of smell were the same as those for taste. However, he was assuredly influenced by the common confusion between the odor of a food and its taste. (An effective demonstration of this confusion is to have blindfolded volunteers bite into a piece of potato and then a piece of apple, while holding their nostrils closed. When the volunteers are asked whether the two foods are the same or different, they will most often describe them as "tasting" the same.) A vigorous experimental demonstration of the contribution of aroma to the recognition of food is provided (Mozell, M.M., B.P. Smith, P.E. Smith, et al Nasal Chemoreception in Flavor Identification. Archives of Otolaryngology, 90, 367 (1979).)

Zwaademaker[68] was the first to provide a systematic classification of odor qualities. His classification included the qualities ethereal (fruits), aromatic (spices), ambrosiac (musk), fragrant (flowers), aliaceous (chlorine), emphyreumatic (coffee), hicine (goaty), foul (fresh marigolds) and nauseous (feces). Another early attempt at classifying olfactory qualities was made by Henning.[69] Like his tetrahedron for taste, Henning proposed a geometrical solid, the smell prism, to represent olfactory qualities (Figure 3). In the smell prism, the six primary qualities are located at the corners, while complex odors are located on the surfaces.
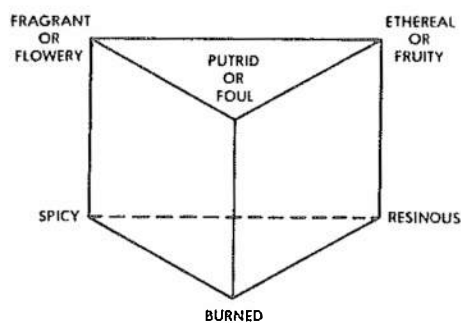
Figure 3. Henning's smell prism.

A still more recent classification of odor qualities was developed by Crocker and Henderson.[70] They suggested the existence of four basic qualities: fragrant, acid, burnt and caprylic, each of which may be present in complex odors, and each of which can be rated on a nine-point (0-8) intensity scale. Odors within this system are represented by a four-digit number ranging from 0000 to 8888. For example, vanillin is designated as fragrant in degree six, acid in degree one, burnt in degree one and caprylic

[68]H. Zwaardemaker. Die Physiologie des Geruchs. Leipzig: Engelmann, 1895.

[69]H. Henning. Der Geruch. Leipzig: Barth, 1916.

[70]E.C. Crocker and L.F. Henderson. Analysis and classification of odors. Am. Perfumer Essent. Oil Rev., 22, 325 (1927).

in degree three; it is represented by a number 6113. Other food and nonfood odor designations are listed in Table 1, taken from the Odor Directory published by Crocker and Dillon.[71]

Table 1. Odor classification numbers and descriptions for some selected odorants (from Crocker and Dillon[71])

Odor Number	Material	Odor Description
3111	Benzyl Benzoate	Almost odorless
3211	Diethyl Phthalate	Almost odorless
4412	Farnesol	Slightly fruity, rosy
6113	Vanillin	Slightly musty, fragrant
8223	Methyl Salicylate	Fragrant, minty, fruity
5333	Oil Grapefruit	Floral, citrusy
7333	Oil Lime, distilled	Floral, citrusy
8633	Oil Verbena	Heavy citrus, very fragrant
7563	Oil Clove	Spicy, fruity, woody
7473	Oil Nutmeg	Spicy, fruity, woody
8624	Cyclohexyl Butyrate	Heavy, jasmine-like, spicy
8674	Oil Labdanum	Heavy, powerful, resinous, woody
7725	Amyl Butyrate	Sharp, estery, fruity
7245	Ethyl Salicylate	Similar to methyl salicylate
7455	Eugenol	Heavy, musty, spicy
6475	Oil Black Pepper	Musty, woody, resinous
4295	Hexyl Salicylate	Phenoic, slightly thyme-like
7286	Oil Bitter Almond	Heavy, burnt, pungent odor
6246	Menthol	Strong cooling effect
6737	Amyl Acetate	Heavy, fatty, fruity
6467	Citronellal	Heavy, musty, fruity
3328	Tincture Amergris	Mild, animal odor
6238	Indol	Powerful, somewhat like civet
6368	Oil Caraway	Heavy, herby, burnt

[71]E.C. Crocker and F.N. Dillon. Odor directory. Am. Perfumer Essent. Oil Rev. (1949).

In general, olfactory classification schemes have had limited success. This is, undoubtedly, due to the difficulty in describing thousands of different odorants in terms of some limited set of sensory descriptors. Of additional difficulty is the problem of identifying the attributes of the stimulus that are essential for stimulation or that determine odor quality. Some of the molecular properties of the stimulus that have been implicated in this role are (1) the stereochemical geometry of the molecule,[72-74] (2) the frequency of vibration of the molecule,[75-78] (3) the arrangement of peripheral functional groups within the molecule,[79,80] (4) molecular cross section and energy of absorption at the lipid/water interface,[81] (5) the solubilities as revealed by gas chromatographic properties[82,83] and (6) the interactive charge

[72] J.E. Amoore. Stereochemical specificities of human olfactory receptors. Perf. Essent. Oil Record, 43, 321 (1952).

[73] J.E. Amoore and D. Venstrom. Correlations between stereochemical assessments and organoleptic analysis of odorous compounds. In Olfaction and Taste II. T. Hayashi (ed). Oxford: Pergamon, 1967.

[74] J.E. Amoore. Molecular basis of odor. Springfield, IL: Thomas, 1970.

[75] R.H. Wright. Odor and molecular vibration. I: Quantum and thermodynamic considerations. J. Appl. Chem., 4, 611 (1954).

[76] R.H. Wright, C. Reid, and G. Evans. Odor and molecular vibration. III: A new theory of olfactory stimulation. Chem. & Ind., 37, 973 (1956).

[77] R.H. Wright. The Science of Smell. New York: Basic, 1964.

[78] R.H. Wright. Predicting olfactory quality from far infrared spectra. Annals NY Acad. Sci., 237, 129 (1974).

[79] M. Beets. Molecular structure and odor. In Molecular Structure and Organoleptic Quality. Monograph #1. London: Soc. Chem. Ind., 1957.

[80] M. Beets. Odor and molecular constitution. Amer. Perfum., 76, 54 (1961).

[81] H.T. Davies. A theory of the quality of odours. J. Theoret. Biol., 8, 11 (1965).

[82] M. Mozell. Evidence for the differential migration of odorant molecules across the olfactory mucosa. In Olfaction and Taste I. C. Pfaffmann (ed). New York: Rockefeller Univ. Press, 1969.

[83] M. Mozell and M. Jagodowicz. Mechanisms underlying the analysis of odorant quality at the level of the olfactory mucosa. I: spatiotemporal sorption patterns. Annals NY Acad. Sci., 237, 76 (1974).

properties of the stimulus and receptor surfaces.[84] While theories based on these physicochemical properties have all enjoyed popularity at one time or another, the two that provide the most useful perspective for the reader are the stereochemical and vibrational theories.

. The stereochemical theory, as originally proposed by J. E. Amoore, assumed that there were seven basic smell qualities: floral, musky, camphoraceous, pepperminty, ethereal, pungent and putrid. For each of these olfactory qualities, an examination of the geometry of compounds known to possess these qualities led to the proposal that a specific shape and size of stimulant molecule determined its olfactory quality. Furthermore, it was proposed that there was a set of olfactory receptors with corresponding geometries, so that only molecules of a specific size and/or shape would fit into a particular receptor site. For example, since camphoraceous-smelling compounds were observed to be spherical and have a molecular diameter of seven Å , Amoore proposed that the corresponding receptor sites were spherical and had a diameter of $\approx$ seven Å. This lock-and-key schema accounted for complex odors by proposing that some molecules could fit into more than one receptor site. Although initial tests of this theory were promising,[85] more recent data[86,87] have led to a revision of the theory, so that specific, rigid geometries are not required for the molecules and/or receptor sites. In addition, the list of proposed primary odor qualities has been restructured on the basis of studies of specific anosmia (an inability to smell a particular compound). These studies have revealed eight primaries to date: sweaty,[88] spermous,[89] fishy,[90] malty,[91] musky,[92] urinous,[92] minty[93] and camphoraceous.[94,95]

[84]A. Dravnieks and P. Laffort. Physicochemical basis of quantitative and qualitative odor discrimination in humans. In Olfaction and Taste IV. D. Schneider (ed). Stuttgart: Wissench. Verlags-gesellsch, 1972.

[85]J.E. Amoore, J.W. Johnston, Jr., and M. Rubin. The stereochemical theory of odor. Sci. Am., 210, 42 (1964).

[86]R.C. Gesteland, J.Y. Lettvin, and W.H. Pitts. Chemical transmission in the nose of the frog. J. Physiol., 181, 525 (1965).

[87]J.E. Amoore. Psychophysics of odor. Cold Spring Flavour Symposia in Quantitative Biology, 30, 623 (1965).

[88]J.E. Amoore, D. Venstrom, and A.R. Davis. Measurement of specific anosmia. Percept. Motor Skills, 26, 143 (1968).

[89]J.E. Amoore, L.J. Forrester, and R.G. Buttery. Specific anosmia to 1 - Pyrooline: The spermous primary odor. J. Chem. Ecol., 1, 299 (1975).

[90]J.E. Amoore and L.J. Forrester. Specific anosmia to trimethylamine: The fishy primary odor. J. Chem. Ecol., 2, 49 (1976).

In contrast to the stereochemical theory, R.W. Wright has been the major proponent of a vibrational theory of olfaction. By examining the olfactory qualities produced by a large number of volatile stimuli and by comparing these to the dominant vibrational frequencies of the stimulus molecules, he has observed that vibrational frequencies below 700 cm^{-1} are highly correlated with the perceived odor quality of the stimulus. Although several failures in prediction and reports of chance correlations between odor quality and vibrational frequency have been reported,[96] Wright has continued to provide impelling data to support this theory.[97-99]

Numerous attempts have been made to classify olfactory qualities and identify the physiocochemical structures responsible for eliciting these qualities. However, the tremendous discriminatory power of the nose requires a larger number of primaries than those that have been proposed. A simple set of primary qualities, such as those proposed for taste, does not seem to be a likely model for olfaction.

D.   Vision

The importance of vision in the appreciation of food quality derives from the fact that the visual aspects of food establish its initial impression, and may well determine whether the product is chosen for consumption. Visual experience results from stimulation of the receptors (rods and cones) in the retina of the eye by electromagnetic radiation in the range from 380 to 760 nm. When viewed as a wave phenomenon, light can be described in terms of its wavelength, intensity and purity. Corresponding to these physical dimensions of light are three psychological attributes: hue, brightness and saturation. Although the accepted qualitative dimension of visual experience is hue, we can assume a less strict definition and treat color as the qualitative dimension, where color is defined as the combined sensory effect of the wavelength, intensity, and purity of the light striking the eye.

[91] J.E. Amoore, L.J. Forrester, and P. Pelosi. Specific anosmia to isobutyraldehyde: The malty primary odor. Chem. Senses & Flavor, 2, 17 (1976).

[92] J.E. Amoore, P. Pelosi, and L.J. Forrester. Specific anosmias to 5d and rost-16 -en-3 one and w-pentadecalactone: The urinous and musky primary odors. Chem. Senses & Flavor, 2, 401 (1977).

[93] P. Pelosi and R. Viti. Specific anosmia to l-carrone: The minty primary odor. Chem. Senses & Flavor, 3, 331 (1978).

[94] P. Pelosi. Specific anosmia to camphoraceous odorants. In Olfaction and Taste VII. L. LeMaghen and P. MacLeod (eds). London: Information Retrieval, 1977, 70.

[95] P. Pelosi and A.M. Pisanelli. Specific anosmia to 1, 8-cineole: The camphor primary odour. Chem. Senses, 6, 87 (1981).

By definition, color is not an intrinsic aspect of objects, but is the result of light being reflected back to the eye from objects in the visual field. Thus, the redness of a Macintosh apple is determined only by the fact that its surface reflects wavelengths of light in the range from 660 to 720 nm and absorbs all others. A Granny Smith apple, on the other hand, is green, because its surface reflects wavelengths from 500 to 560 nm and absorbs all others.

Historically, colors, like the qualitative dimensions in other senses, have been represented as a solid. Figure 4 is a schematic of what is known as the color spindle. The mid-point (NG) of the spindle represents neutral gray, and the circumference represents different hues. Vectors drawn from neutral gray to any point on the circumference reflect increasing degrees of saturation, and the vertical dimension reflects differences in brightness, with white at the top (W) and black at the bottom (B).
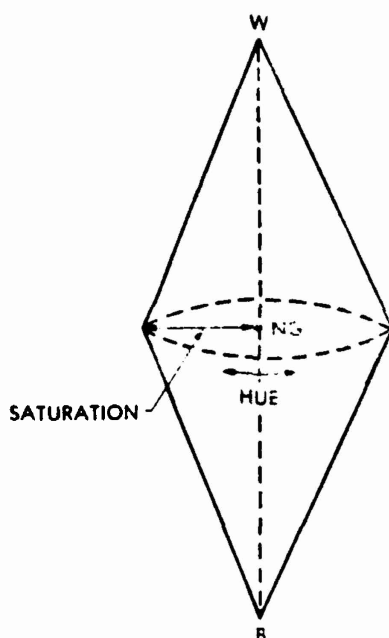
Figure 4. The color spindle.

[96] J.T. Davis. Olfactory theories. In Handbook of Sensory Physiology, Vol. IV, Part 1: Olfaction. L.M. Beidler (ed). New York: Springer-Verlag, 1971.

[97] R.H. Wright. Odor and molecular vibration: Optical isomers. Chem. Senses & Flavor, 3, 35 (1978).

[98] R.H. Wright. The perception of odor intensity: Physics or psychophysics? Chem. Senses & Flavor, 3, 73 (1978).

[99] R.H. Wright. The perception of odor intensity: Physics or psychophysics? II. Chem. Senses & Flavor, 3, 241 (1978).

For use in applied situations, a variety of other color classification schemes have been developed. The most common of these include the Munsell System, the ICI System, the Lovibond System, and the Ostwald System. Details of these systems and their application to the food industry are available in a number of texts.[100-102]

The accepted number of primary qualities (colors) has varied through the years, depending upon the particular theory of color vision that has been popular at the time. For example, the Young-Helmholtz theory proposes that there are three primary colors - **red, green,** and **blue,** each of which corresponds to one of three different types of receptors in the retina of the eye, and these receptors are, in turn, differentially sensitive to three dominant wavelengths of light. In contrast, the Hering Opponent - Colors theory, postulates six paired primaries - **white and black, green and red,** and **yellow and blue.** For each pair of primaries, a receptor mechanism is proposed that contains a metabolic substance that is augmented (anabolism) when stimulated by one primary and depressed (catabolism) when stimulated by the opposing primary. While the latter theory accounts for numerous sensory color phenomena, e.g., color afterimages, the existence of anabolic reactions has yet to be established in humans, and the more recent suggestion[103] that neural excitatory and inhibitory mechanisms may serve as the opposing processes has done little to advance the popularity of this theory.

Also of importance to the consideration of visual primaries is the theory of color vision proposed by Ladd-Franklin. This theory assumes the existence of five primaries - **white, blue, yellow, red** and **green** and proposes a specific evolutionary development for color vision. Unfortunately, as with Hering's theory, physiological and biochemical evidence on receptor substances has cast doubt on the likelihood of this theory.

Although the above theories are important for conceptualizing possible mechanisms of color vision, a series of discoveries made during the last 20 years[104-106] has firmly established the existence of three receptor types in the human retina. Each of these receptors responds best to wavelengths of light in the **red, green** and **blue** regions of the spectrum and provides support to the Young-Helmholtz theory. This physiological evidence has led visual scientists to conclude that there are, in fact, three primary color qualities in humans - **red, green** and **blue.**

[100]D.B. Judd and G. Wyszecki. Color in Business, Science and Industry. New York: Viking, 1963.

[101]G. MacKinney and A. Little. Color of Foods. Westport, CT: AVI Publishing, 1962.

[102]F.J. Francis and F.M. Clydesdale. Food Colorimetry: Theory and Applications. Westport, CT: AVI Publishing, 1975.

[103]F. Geldard. The Human Senses, 2nd ed. New York: Wiley, 1972.

While color is often the major visual component of the appearance of a food, other visual dimensions related to the geometry of the product and to the way in which light reacts at a physical surface are also important. These include gloss or sheen, turbidity, and the perceived size and shape of the product.

When light strikes an object (food or beverage), it is transmitted, absorbed or reflected. Figure 5 depicts these three possibilities (note that refraction is a special case of transmission in which the angle of incident light is different than the angle of transmitted light). Almost all foods and beverages absorb some light. The remainder of the incident light is reflected back or transmitted. When incident light is reflected in all directions, a dull or flat finish is perceived in the object. However, when light is reflected back in only a single direction, a glossy finish is perceived. Gloss is an important attribute of the appearance of such foods as apples, cherries, and glazes of pastries and is often called "shine" or "polish."

INCIDENT LIGHT   TRANSMITTED LIGHT
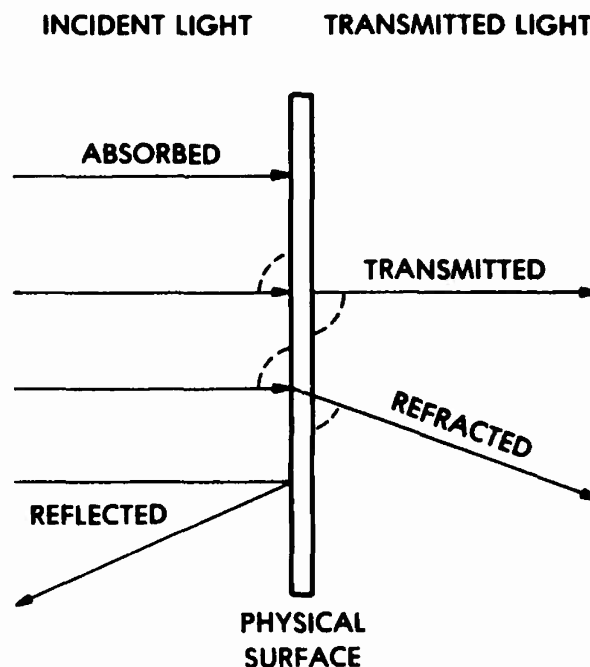
Figure 5. Reactions of incident light at at surface.

[104]W.A.H. Rushton. Visual pigments in the colour blind. Nature, 182, 690 (1958).

[105]W.B. Marks, W.H. Dobelle, and E.F. MacNichol, Jr. Visual pigments of single primate cones. Science, 143, 1181 (1964).

[106]G. Wald. The receptors of human color vision. Science, 145, 1007 (1964).

[107]J. Locke. An Essay Concerning Human Understanding: In Four Books. London, 1690.

Incident light that is not absorbed or reflected is transmitted through the object. Most beverages transmit significant amounts of light. The greater the amount transmitted, the more **translucent** is the object. In addition to the total amount of light being transmitted, the light may either pass directly through the medium or be scattered by particles contained in the medium. When scattering occurs, as in orange juice or other suspensions, the sensory attribute of **turbidity** is perceived in the object.

Size and shape are visual attributes of all foods and were designated as "primary" qualities by Locke[107] because of their intrinsic nature in all objects. In the case of naturally occurring food products, these attributes are determined by nature, and the role of quality assurance consists of identifying and discarding aberrant sizes and shapes. In formulated products, size and shape are under the control of the processor. In both cases, judgments of size (extent, area, volume) and shape can be made subjectively or with the use of instrumentation. The ability to measure precisely the size and shape of food objects using objective means (sorting devices) has resulted in a heavy reliance on these methods for quality control of mass-produced items. Nevertheless, subjective evaluations of size and shape are frequently used in small-scale quality control operations, and the sensory assessment of these attributes is still important in research and development efforts aimed at producing visually appealing products.

E. Audition

Audition is the subjective experience resulting from stimulation of the receptors located in the cochlea of the ear by sound waves transmitted through air, water, bone or other elastic media. Although audition is not considered to be a food sense, the sounds emitted during mastication play a significant role in the perception of food quality for many products, including potato chips, celery, carrots and other crisp foods.

Sound is a wave phenomenon, and like light, the amplitude, wavelength, and purity of the waveform define three psychological dimensions – **loudness**, **pitch** and **timbre**. As in vision, the wavelength (or its inverse, frequency) determines the primary qualitative dimension. In humans, variations in pitch can be perceived for frequencies ranging from 20 to 20,000 Hz. Combinations of different frequencies produce the dimension of timbre, much like combinations of different frequencies of light produce the dimension of saturation. However, unlike light waves, a small set of primary frequencies cannot be used to generate the entire sound spectrum. Thus, there are no true primary qualities in audition, but rather a continuous series of qualitatively different pitches.

The study of the effects of sound on food quality is just now emerging, therefore, knowledge of auditory theory is not essential for the reader interested in sensory food quality assessment. However, one should be aware that current theory is based on a combination of two older theories – (1) Helmholz's resonance theory, postulating that different frequencies of sound resonate auditory receptors located at different places along the basilar membrane (receptor surface) of the cochlea and (2) Rutherford's frequency

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theory, postulating that the basilar membrane responds like a telephone, receiving and sending all frequencies of sound waves to the brain, where a Fourier analysis of the compound waveform occurs. Current theory, known as **traveling wave theory**, affirms that traveling waves of sound cross the basilar membrane and produce maximum stimulation of receptors at specific places along the membrane, dependent upon the frequency of stimulation.

Although the auditory component of certain foods, e.g., celery, apples and crackers, has been known to have a effect on their acceptability for some time, relatively little research has been undertaken, until recently, to characterize foods or their texture by sounds. Of notable early exception were studies[108-110] in which sounds produced by chewing of foods were recorded and analyzed in terms of their amplitude, frequency and duration. These data showed differences among the sounds made by different foods, and, on the basis of these differences, some classification of foods was possible. More recently, acoustical analysis of food-crushing sounds has been undertaken in the search for an objective method to assess the crispness and crunchiness of foods.[111-117] The progress now being made in this area has finally opened the way to the acceptance of audition as a true "food sense."

[108]B.K. Drake. Food crushing sounds. Comparisons of subjective and objective data. J. Food Sci., 30, 556 (1965).

[109]B.K. Drake. Food crushing sounds. An introductory study. J. Food Sci., 28, 233 (1963).

[110]B.K. Drake. On the biorheology of human mastication: An amplitude – frequency-time analysis of food crushing sounds. Biorheology, 3, 21 (1965).

[111]Y. Anderson, B. Drake, A. Granquist, L. Halliden, B. Johansson, R.M. Pangborn, and D. Akesson. Fracture force, hardness and brittleness in crisp bread, with a generalized regression analysis approach to instrumental-sensory comparisons. J. Texture Stud. 4, 119 (1973).

[112]B. Drake and L. Halliden. Food crushing sounds: An analytical approach. Rheol. Acta, 13, 608 (1974).

[113]Z.M. Vickers and M.C. Bourne. A psychoacoustical theory of crispness. J. Food Sci., 41, 1158 (1976).

[114]Z.M. Vickers. Crispness and crunchiness of foods. In Food Texture and Rheology. P. Sherman (ed). London: Academic Press, 1979.

[115]Z.M. Vickers. Relationships between sensory crispness and other sensory and instrumental parameters. J. Texture Studies, 11, 291 (1980).

[116]Z.M. Vickers and S.S. Wasserman. Sensory qualities of food sounds based on individual perceptions. J. Texture Stud., 10, 319 (1979).

[117]C.M. Christensen and Z.M. Vickers. Relationships of chewing sounds to judgments of food crispness. J. Food Sci., 46, 574 (1981).

F. Kinesthesis and Somesthesis

Kinesthesis (literally, "feeling of motion") refers to the sensations of limb position and movement and is mediated by receptors located in the muscles. tendons and joints. Somesthesis refers to the sensations arising from receptors located in the skin. These include sensations of pressure (touch). pain and temperature. Together, somesthesis and kinesthesis mediate the remainder of oral-sensory experiences: perception of food texture, temperature and mouthfeel.

The receptors giving information about passive movement imparted to the limbs were once believed to be primarily located in muscles. However, at the turn of the century, it was demonstrated that these receptors are located with the joints.[118,119] Muscle receptors, while providing relatively little information during passive limb movement, do provide significant kinesthetic information during active (self-initiated) limb movement and when resistance to movement is met. Because foods in the mouth provide continuous resistance to active jaw movements, both kinesthetic joint and muscle receptors are involved in the perception of food texture.

The receptors for kinesthetic sensibility are numerous and include spindle organs (also called stretch receptors) in muscles, Golgi organs in joints and tendons. Pacinian corpuscles in the fascia of muscle and in joints, Ruffini corpuscles in joints, and free nerve-endings in muscles, tendons and joints. In the mouth, the muscles involved in kinesthetic perception are the intrinsic and extrinsic muscles of the tongue (extrinsic muscles join the tongue to the cranium; intrinsic muscles are those contained wholly within the tongue) and the masticatory muscles, which move the mandible. Although several early investigators suggested the absence of spindle organs in intrinsic and external tongue muscles[120-121] and in the lateral pterygoid masticatory

[118]A. Goldscheider. Untersuchungen uber den muskelsinn. I. Ueber die bewegungsempfindung. In Gesammelte Abhandlungen von A. Goldscheider, Vol. II. Leipzig: Barth, 1898.

[119]A. Goldscheider. Untersuchungen uber den muskelsinn. II. Ueber die empfingdung der schwere und des widerstandes. In Gesammelte Abhandlungen von A. Goldscheider, Vol. II. Leipzig: Barth, 1898.

[120]E.E. Hewer. Development of nerve endings in human fetus. J. Anat., 69, 369 (1935).

[121]G. Weddell and J.A. Harpman. Neurohistological basis for sensation of pain provoked from deep fascia tendon and periasteum. J. Neurol. Psychiat., 3, 319 (1948).

[122]M.E. Law. Lingual proprioception in pig. dog and cat. Nature, 174, 1107 (1954).

muscle,[123-125] more recent studies have established that spindle organs *do* exist in these structures.[126-130]

The primary joint receptors providing kinesthetic information from the mouth are located in the temporomandibular joint, which connects the mandible to the skull. An excellent review of the functional anatomy and physiology of the tongue and mouth of mammals has been provided by Halpern,[131] and several important contributions to the study of oral kinesthesis can be found in the proceedings of several symposia edited by Kawamura[132] and Bosma.[133]

[123]R. Freimon. Untersuchung uber zahl und anordnung der muskel indeln in der kaumuskeln des menschen. Anat. Anz., 100, 258 (1954).

[124]S. Cooper. Muscle spindles and other muscle receptors. In *The Structure and Function of Muscle*, Vol. 1. G.H. Bourne (ed). New York: Academic Press, 1960, 381.

[125]A.S.T. Frank. Studies on the innervation of the temporomandibular joint and lateral pterygoid muscle in animals. J. Dent. Res., 43, 947 (1964).

[126]G.L.J.M. Honce. An investigation on the presence of muscle spindles in the human lateral pterygoid muscle. Nether. Dent. J., 73, 43 (1966).

[127]H.J. Gill. Neuromuscular spindles in human lateral pterygoid muscles. J. Anat., 109, 157 (1971).

[128]M.T. Rakhawy, S.H. Shehata, and Z.H. Badawy. The proprioceptive innervation of the lateral pterygoid muscle in man and some other mammals. Acta Anat., 79, 581 (1971).

[129]S. Cooper. Muscle spindles in the intrinsic muscles of the human tongue. J. Physiol., 122, 193 (1953).

[130]L.B. Walker, Jr. and M.D. Rajagopal. Neuromuscular spindles in the human tongue. Anat. Rec., 133, 438 (1959).

[131]B. Halpern. Functional anatomy of the tongue and mouth of mammals. In *Drinking Behavior, Oral Stimulation, Reinforcement and Preference*. J.A.W.M.. Weijnen and J. Mendelson (eds). New York: Plenum, 1977.

[132]Y. Kawamura. Advances in Oral Physiology. Y. Kawamura (ed). Osaka: Amsa Catalog, 1968.

[133]J.F. Bosma. Oral Sensation and Perception, Vols. I, II, III and IV. J.F. Bosma (ed). Springfield, IL: Thomas, 1967, 1970, 1972, 1973.

Concerning the somesthetic sense receptors, oral structures differ greatly in their sensitivity to simple pressure or touch. Greatest sensitivity is found on the lips and tip of the tongue; sensitivity progressively decreases in structures or areas more posterior in the oral cavity.[134-137] In hairy skin, the somesthetic receptors for simple pressure or touch are hair follicle endings. However, in glabrous skin (nonhairy) and in the oral mucosa, Meissner corpuscles and Krause end-bulbs serve as the tactile receptors.[138-141] Nerve impulses resulting from pressure applied to the teeth originate in the periodontal membrane[142] and the tactile receptors located in this tissue are identical to those found in the mucosa.[143]

[134]R.F. Grossman. Methods of determining oral tactile experience. In J.F. Bosma (ed). Symposium on Oral Sensation and Perception. Springfield, IL: Thomas, 1967, 141.

[135]R.L. Henkin and V. Banks. Tactile perception on the tongue, palate and the hand of normal man. In Symposium on Oral Sensation and Perception. J.F. Bosma (ed). Springfield, IL: Thomas, 1967, 182.

[136]R.L. Ringel. Oral region two-point discrimination in normal and myopathic subjects. In Second Symposium on Oral Sensation and Perception. J.F. Bosma (ed). Springfield, IL: Thomas, 1970, 309.

[137]R.L. Ringel. Studies on oral region textural perception. In Second Symposium on Oral Sensation and Perception. J.T. Bosma (ed). Springfield, IL: Thomas, 1967, 323.

[138]A.D. Dixon. Nerve plecuses in the oral mucosa. J. Dent. Res., 36, 807 (1957).

[139]A.D. Dixon. Sensory nerve terminations in the oral mucosa. Arch. Oral Biol., 5, 105 (1961).

[140]T.H. Williams and A.D. Dixon. The intrinsic innervation of the soft palate. J. Anat., 97, 259 (1963).

[141]R.F. Grossman and B.F. Hattis. Oral mucosa sensory innervation and sensory experience: A review. In Symposium on Oral Sensation and Perception. J.F. Bosma (ed). Springfield, IL: Thomas, 1967, 5.

[142]C. Pfaffmann. Afferent impulses from the teeth due to pressure and noxious stimulation. J. Physiol., 97, 207 (1939).

[143]B. Kerebel. Innervation of human periodontium. Actual. Odonto. Stomat., 71, 289 (1965).

The primary receptors for temperature (thermal) sensitivity remain to be positively identified. Historically, the Krause end-bulb has been considered as the receptor for cold and the Ruffini cylinder as the receptor for hot. However, it now seems clear that neither of these receptor types subserves thermal perception[144,145] and that free nerve endings are the more likely candidates. Studies of thermal sensitivity of oral regions have been few, but available data suggest that the lips, tip of the tongue and hard palate have greater sensitivity to warming and cooling than do other oral areas.[141]

The primary receptors for perception of pain have long been held to be free nerve endings in the skin; however, current opinion is that a variety of high-threshold mechanical and thermal receptors are responsible for mediating pain sensation.[146] Interesting, however, is the fact that many parts of the oral cavity are relatively analgesic. These include the mucous lining of the cheeks, the posterior tongue and mouth and the lower part of the uvula. Other areas of the mouth and nose contain significant numbers of nociceptors (pain receptors) and can give rise to painful sensations as a result of intense tactile, thermal or chemical stimuli. The latter sensations contribute to the overall impact of spicy foods (those containing black pepper, chili pepper, ginger root, etc.) through such perceptual dimensions as "pungency," "stinging," "biting," "chemical cool" and "chemical warmth." These sensations, mediated by the trigeminal nerve, are frequently described as belonging to the "common chemical sense," since they are elicited by chemical irritants. Moreover, the relationships of these sensations to taste and smell have been investigated to assess their independent contribution to the perception and appreciation of foods.[147-149]

[144]K.H. Andres and M. von During. Morphology of cutaneous receptors. In Handbook of Sensory Physiology, Vol. II: Somatosensory System. A. Iggo (ed). New York: Springer-Verlag, 1973.

[145]H. Hensel. Cutaneous thermoreceptors. In Handbook of Sensory Physiology. Vol. II: Somatosensory System. A. Iggo (ed). New York: Springer-Verlag, 1977, 29.

[146]P.R. Burgess and E.R. Perl. Cutaneous mechanoreceptors and nociceptors. In Handbook of Sensory Physiology. Vol. II: Somatosensory System. A. Iggo (ed). New York: Springer-Verlag, 1977, 29.

[147]W.S. Cain. Contribution of the trigeminal nerve to perceived odor magnitude. Ann. N.Y. Acad. Sci., 237, 28 (1974).

[148]W.S. Cain. Olfaction and the common chemical sense: Some psychophysical contrasts. Sensory Processes, 1, 57 (1976).

[149]V.S. Gouindarajan. Pungency: The stimuli and their evaluation. In Food Taste Chemistry. J.C. Boudreau (ed). Washington, DC: American Chemical Society, 1979, 53.

The task of identifying primary qualities in the somesthetic and kinesthetic senses is a difficult one. The difficulty is partly due to the fact that researchers do not all agree on whether such differences as those between pressure, temperature and pain are differences in **modalities** or differences in **qualities**. In addition, such terms as touch, tickle, vibration and itch refer to different sensations; yet, it is not clear whether these differences are strictly qualitative or due, in part, to quantitative differences in the intensity of the sensations. Thus, of greater importance to issues of food quality assessment than the discussion of qualities in the kinesthetic and somesthetic senses is a consideration of the integrated sensory experiences resulting from the stimulation of these senses by foods in the mouth, i.e, the qualities of food **texture**.

The most comprehensive attempt at identifying and classifying food texture characteristics is the system developed at General Foods Corp.[150,151] The classification system places textural qualities into three categories: (1) **mechanical** - those characteristics that are related to the responses of foods to applied forces: (2) **geometrical** - those characteristics that are related to the geometrical arrangement of the food matrix, e.g., size, shape and orientation of particles, and (3) **moisture** and **fat-related** - those characteristics that are associated with the water and fat content of food. Within this system the mechanical characteristics of texture have been divided into primary and secondary, the secondary characteristics being composites of the primary characteristics. The geometrical characteristics are also of two types - those related to the size and shape of particles and those related to the orientation of particles in the food. Table 2 shows the complete classification system. Greater detail on the sensory measurement of texture will be provided in a later section.

Table 2. Classification of textural characteristics, based on the General Foods' texture profile approach

QUALITATIVE ATTRIBUTES OF TEXTURE

A. MECHANICAL:

Hardness	Fracturability
Cohesiveness	Chewiness
Viscosity	Gumminess

B. GEOMETRICAL:

SIZE & SHAPE: Powdery, Chalky, Gritty, Beady, Grainy, Coarse, Lumpy

ORIENTATION: Flaky, Fibrous, Pulpy, Cellular, Aerated, Puffy, Crystalline

C. MOISTURE/FAT:

Moistness	Oiliness
	Greasiness

[150]M.A. Brandt, E.Z. Skinner, and J.A. Coleman. Texture profile method. J. Food Sci.. 28, 404 (1963).

[151]A.S. Szczesniak. Classification of textural characteristics. J. Food Sci., 28, 385 (1963).

G.   Hedonic Quality

In addition to the classical sensory modalities and qualities, a hedonic or affective dimension is associated with foods.[152] The perception of the pleasantness or unpleasantness of a food results from a weighing of the sensory information available about the food and the organism's past experiences with that food. This latter aspect of hedonic quality, its dependence on prior learning, is important, since it means that an individual's judgment of the hedonic aspect of food may be only partly related to the sensory "character" of the food. A good example of this is the preference of individuals for different wines. Many people prefer the less expensive, sweeter and more fruity wines to the classic vintage wines which may have a drier character, and are considered to be of better quality. Another example is the preference for pungent foods, where it has been shown that children will come to accept and prefer "hot" foods, such as chili peppers, upon repeated exposure to them.[153-155]

The history of hedonic measurement has been traced by Beebe-Center[156] and his work provides an excellent survey of early research in this area. However, the modern history of the topic can be traced to research conducted at the U.S. Army's Quartermaster Food and Container Institute beginning in the late 1940's. Out of this work came an instrument for measuring food likes and dislikes that uses a structured 9-point scale.[157-158] The development of the "hedonic scale," as it has come to be called, resulted in an unheralded examination of the many factors affecting food acceptibility that has continued to the present day.

[152]C. Pfaffmann. The pleasures of sensation. Psych. Rev., 67, 253 (1960).

[153]P. Rozin and A.E. Fallon. The acquisition of likes and dislikes for foods. In J. Solms and R.L. Hall (eds). Criteria of Food Acceptance: How Man Chooses What He Eats. A Symposium. Zurich: Forster, 1980.

[154]P. Rozin and D. Schiller. The nature and acquisition of a preference for chili pepper by humans. Motivation and Emotion, 4, 77 (1980).

[155]P. Rozin, M. Mark, and D. Schiller. The role of desensitization to capsaicin in chili pepper ingestion and preference. Chem. Senses, 6, 23 (1981).

[156]J.G. Beebe-Center. The Psychology of Pleasantness and Unpleasantness. Princeton, NJ: Von Nostrand, 1932.

[157]D.R. Peryam and N.F. Giaradot. Advanced taste-test method. Food Eng., 58, 194 (1952).

[158]D.R. Peryam and F.J. Pilgrim. Hedonic scale method of measuring food preferences. Food Technol., 9, 11 (1957).

In contrast to the fundamental sensory qualities, the hedonic dimension is complicated by the fact that it may actually be two separate psychological dimensions: that is, stimuli that are unpleasant or disliked appear to be qualitatively different from stimuli that are pleasant or liked. Disliked stimuli do not appear to be simply quantitatively less pleasant or less liked. Also contrasting with basic sensory qualities, wherein the perceived magnitude of a sensation is monotonic with the physical intensity of the stimulus, the hedonic magnitude of a stimulus usually follows an inverted U function, peaking at intermediate stimulus intensities.[159-161]

Most frequently, the hedonic quality of food is assessed through either food acceptance or food preference testing. Food acceptance can be defined as the hedonic response to a food item that is presented for evaluation. Food preference, on the other hand, is usually defined as the choice of one food item over another but is frequently assessed attitudinally, as the hedonic response to a food name. Most preference tests can be conducted using the same methods employed in acceptance tests, and significant amounts of data on the food preferences of military personnel[162-164] and other population groups have been made available via these methods.

While the same measurement scales can be used for both acceptance and preference testing, the relationship between acceptance and preference is distinctly nonlinear. In a recent study,[165] a comparison of preference ratings with acceptability ratings demonstrated a regression of acceptability

[159]W. Wundt. Grudzuge der Physiologischen Psychologie. Leipzig: Engelmann, 1874.

[160]W. Wundt. Outlines of Psychology. C.H. Judd, Trans. Leipzig: Engelmann, 1907.

[161]D.E. Berlyne. Aesthetics and Psychobiology. New York: Appleton, 1971.

[162]H.L. Meiselman, D. Waterman, and L.E. Symington. Armed Forces Food Preferences. Technical Report 75-63-FSL, U.S. Army Natick Research and Development Center, Natick, MA, December 1974 (AD A110 512).

[163]H.L. Meiselman and D. Waterman. Food preferences of enlisted personnel in the Armed Forces. J. Am. Diet. Assoc., 73, 621 (1978).

[164]H.L. Meiselman. The role of sweetness in the food preference of young adults. In Taste and Development: The Genesis of Sweet Preference. J. Weiffenbach (ed). National Institute of Dental Research, DHEW Publication No. 77-1068. Rockville, MD: U.S. Department of Health, Education and Welfare, National Institutes of Health, 1977, 269.

[165]A.V. Cardello and O. Maller. Relationships between food preferences and food acceptance ratings. J. Food Sci., 47, 1553 (1982).

ratings toward the mean, relative to preference ratings. That is, for any food item that was rated extremely high or extremely low on preference, acceptability ratings of the actual food item by individuals tended more toward neutrality. Thus, it seems that our perceived likes and dislikes for foods, as reflected in preference ratings, are our sensory "ideals," and that actual preparations of the food item usually evoke a more moderate reaction.

III. THE QUALITATIVE DESCRIPTION OF SENSORY DATA:
APPLIED METHODS

Due to the multimodal nature of food, it is not surprising that certain sensory qualities of food influence the perception of other qualities. The most frequently investigated of these cross-sensory effects have been the effects of food color on other sensory attributes. Effects of color have been shown on the recognition and perceived intensity of basic taste qualities,[166-168] as well as on the detection, identification and perceived intensity of food flavors.[169-172] In addition, textural qualities have been shown to

[166] J.A. Maga. Influence of color on taste thresholds. Chem. Senses & Flavor, 1, 115 (1974).

[167] R.M. Pangborn. Influence of color on the discrimination of sweetness. Am. J. Psychol., 73, 229 (1960).

[168] A.S. Kostyla and F.M. Clydesdale. The psychophysical relationships between color and flavor. CRC Critical Reviews in Food Sci. and Nutrition Dec., 303 (1978).

[169] H.C. Moir. Some observations on the appreciation of flavour in foodstuffs. Chem. Ind., 55, 145 (1936).

[170] J.L. Kanig. Mental impact of colors in foods studied. Food Field Reporter, 23, 57 (1955).

[171] R.L. Hall. Flavor study approaches at McCormick & Company, Inc. In Flavor Research and Food Acceptance. New York: Reinhold, 1958, 224.

[172] C.N. Dubose, A.V. Cardello, and O. Maller. Effects of colorants and flavorants on identification, perceived flavor intensity, and hedonic quality of fruit-flavored beverages and cake. J. Food Sci., 45, 1393 (1980).

affect both taste and odor judgments,[173-183] and, inversely, taste has been shown to have effects on perceived texture.[184] Temperature has also been

[173]H. Stone and S. Oliver. Effect of viscosity on the detection of relative sweetness intensity of sucrose solutions. J. Food Sci., 31, 129 (1966).

[174]P. Arabie and H. Moskowitz. The effects of viscosity upon perceived sweetness. Percept. & Psychophys., 9, 410 (1971).

[175]H. Moskowitz and P. Arabie. Taste intensity as a function of stimulus concentration and solvent viscosity. J. Texture Stud., 1, 502 (1970).

[176]S.G. Marshall and M. Vaisey. Sweetness perception in relation to some textural characteristics of hydrocolloid gels. J. Texture Stud., 3, 173 (1972).

[177]M. Vaisey, R. Brunon, and J. Cooper. Some sensory effects of hydrocolloid sols on sweetness. J. Food Sci., 34, 397 (1969).

[178]R.M. Pangborn and A.S. Szczesniak. Effect of hydrocolloids and viscosity on flavor and odor intensities of aromatic flavor compounds. J. Texture Stud., 4, 467 (1974).

[179]C.M. Christensen. Texture-taste interactions. Cereal Foods World, 22, 243 (1977).

[180]A.O. Mackey and K. Valass. The discernment of primary tastes in the presence of different food textures. Food Technol., 10, 238 (1956).

[181]R.M. Pangborn, I.M. Trabue, and A.S. Szczesniak. Effect of hydrocolloids on oral viscosity and basic taste intensities. J. Texture Stud., 4, 467 (1974).

[182]C.M. Christensen. Effects of solution viscosity on perceived saltiness and sweetness. Percept. & Psychophys., 28, 347 (1980).

[183]K. Paulus and E.M. Haas. The influence of solvent viscosity on the threshold values of primary tastes. Chem. Senses, 5, 23 (1980).

[184]C.M. Christensen. Effects of taste quality and intensity on oral perception of viscosity. Percept. and Psychophys., 28, 315 (1980).

shown to affect taste judgments,[185-188] while taste and smell have been shown to have effects on one another.[189-191] Numerous other studies of cross-sensory interactions have been reviewed[192] and a renewed interest in synesthesia (sensation experienced in one modality following stimulation of a different modality) has appeared.[193-194]

The interrelationships among the senses complicate the analysis of sensations into specific component qualities, and although the attempts at identifying basic sensory qualities have met with considerable success, the challenge of reducing all flavor or texture sensations to a small set of primaries is an extremely difficult one, especially considering the broad spectrum of sensations evoked by foods. For this reason, many food companies have relied on "expert" tasters to describe and evaluate the sensory characteristics of their products. These experts, through years of exposure

[185]R.M. Pangborn, R.B. Chrisp, and L.L. Bertolero. Gustatory salivary, and oral thermal responses to solutions of sodium chloride at four temperatures. Percept. and Psychophys., 8, 69 (1970).

[186]H.R. Moskowitz. Effects of solution temperature on taste intensity in humans. Physiol. & Behav., 10, 289 (1973).

[187]P.M. McBurney, V.B. Collings, and L.M. Glanz. Temperature dependence of human taste responses. Physiol. & Behav., 11, 89 (1973).

[188]K. Paulus and A.M. Reisch. The influence of temperature on the threshold values of primary tastes. Chem. Senses, 5, 11 (1980).

[189]L.M. Bartoshuk. Taste mixtures: Is mixture suppression related to compression? Physiol. & Behav., 14, 643 (1975).

[190]L.M. Bartoshuk and C.T. Cleveland. Mixtures of substances with similar tastes. A test of a psychophysical model of taste mixture interactions. Sensory Process., 1, 177 (1977).

[191]C. Murphy, W. Cain, and L. Bartoshuk. Mutual action of taste and olfaction. Sensory Process., 1, 204 (1977).

[192]H. Stone and R.M. Pangborn. Intercorrelation of the senses. In Basic Principles of Sensory Evaluation, ASTM STP 433. Philadelphia. PA: American Society for Testing and Materials, 1968, 30.

[193]L.E. Marks. The Unity of the Senses. New York: Academic Press, 1978.

[194]L.E. Marks. Bright sneezes and dark coughs, loud sunlight and soft moonlight. J. Exp. Psych.: Hum. Percept. & Perform., 8, 177 (1982).

to the product and continued judgmental evaluation of its sensory characteristics, become the ultimate instruments in assessing the quality of the product. Moreover, in the areas of flavor and texture, descriptive approaches have been developed that rely on the use of **trained** panels of judges, who define, describe and evaluate the sensory attributes of importance to the product. Where applicable, these panels use the same primary qualities that have been identified in the preceeding sections; but many of their descriptive analyses are based upon **introspection** and the development of a unique terminology based on consensual agreement and definition.

A. Descriptive Flavor Analysis

The best known of the applied descriptive methods is the flavor profile technique developed by Arthur D. Little Co. of Cambridge, MA. The basic method involves the use of a panel of six to eight judges. Judges are selected for the panel on the basis of (1) availability, (2) interest, (3) personality factors and (4) possession of "normal" taste and smell sensitivity (the latter being determined by taste and odor threshold tests). Panelists undergo a 6- to 12-month training period during which the basic principles of taste and smell physiology and psychophysics are covered, and extensive training is given in flavor description, using established reference standards. In addition to panel members, a panel leader is selected, whose job is to coordinate panel meetings, lead profile panel discussions, obtain the consensus of the panel and communicate results to users of the panel data.

The basic flavor profile method, as outlined by Cairncross and Sjostrom[195] and by Caul[196] involves the evaluation of test products by individual panel members, followed by a group discussion. Panelists (1) dr ine the qualitative notes (attributes) of aroma, taste, flavor and mouthfeel that are apparent in the product; (2) indicate the order of perception of each of these "notes," (3) define any aftertastes that may be present; (4) rate each note for its intensity; and (5) rate the overall impression or quality of the product ("amplitude"). The intensity of any note or dimension is rated on a labeled scale. The scale specified by the method consists of the following labeled intensity categories:

    0 = not present
)(= threshold
    1 = slight
    2 = moderate
    3 = strong

[195]S.E. Cairncross and L.B. Sjostrom. Flavor profiles - a new approach to flavor problems. Food Technol., 4, 308 (1950).

[196]J.F. Caul. The profile method of flavor analysis. In Advances in Food Research, 17. E. Mrak and G.F. Stewart (eds). New York: Academic Press, 1956.

Figure 6 shows a typical representation of flavor profile data for four commercial brands of catsup.[197] The order of appearance of each note is designated by the clockwise order of vectors and corresponds to the order of flavor notes listed at the bottom of the profiles. The magnitude (length) of each vector reflects the intensity of the note, and the size of the semicircle indicates the total perceived flavor. Differences in flavor among the various samples are easily appreciated when this visual representation is used.

Although the flavor profile approach is widely used in the food industry, it has several disadvantages. The most critical disadvantages are: (1) the time and cost of developing and maintaining a panel, (2) the use of symbols in the scaling procedure, such as)(, that preclude the calculation of means or the use of other descriptive or inferential statistics and (3) the use of open discussion among panelists, which may allow group opinion to bias individual panelists.

Recently, an alternative approach to the Arthur D. Little Flavor Profile was developed at the Stanford Research Institute.[198] This technique, known as Quantitative Descriptive Analysis (Q.D.A.), has the advantage of allowing quantification of the sensory judgments in a way that can be easily evaluated by statistical methods. While Q.D.A. relies on trained panelists to define the qualitative attributes of a food product, all evaluations by panelists are made in individual testing booths, thereby limiting the influence of group dynamics. In addition, repeated judgments are made by panelists so that both individual and group performance can be statistically evaluated. Also, intensity judgments are made using a labeled graphic line scale. By eliminating symbols from the scaling procedure, means can be directly calculated and statistical analyses can be made of the data.[199] Since this scaling technique is an equal-interval scale, it has advantages over category scales, which will be discussed in a later section.

[197]Anonymous. Flavor profile describes food flavors in easily understandable terms. Food Process., 11, 30 (1950).

[198]H. Stone, J.L. Sidel, S. Oliver, A. Woolsey, and R.C. Singleton. Sensory evaluation by qualitative descriptive analysis. Food Technol., 24, 28 (1974).

[199]J.M. Mecredy, J.C. Sonnemann, and S.J. Lehmann. Sensory profiling of beer by a modified QDA method. Food Technol., 28, 36 (1974).

A

SWEET	3
GINGER	3
ALLSPICE	)(
TOMATO	)(
SOUR	2
SALT	1

B

BAKED BEAN THIOL	2
SWEET	1
SOUR	1
BUTYRIC-VALERIC	2
SALT	)(
PEPPER BITE	3
ASTRINGENT	1

C

SWEET	2
SALT	2
SOUR	1
TOMATO	1
SPICE COMPLEX	)(

D

SWEET	3
SALT	2
MOLASSES	2
SOUR	1
COOKED TOMATO	)(
SPICE COMPLEX	)(
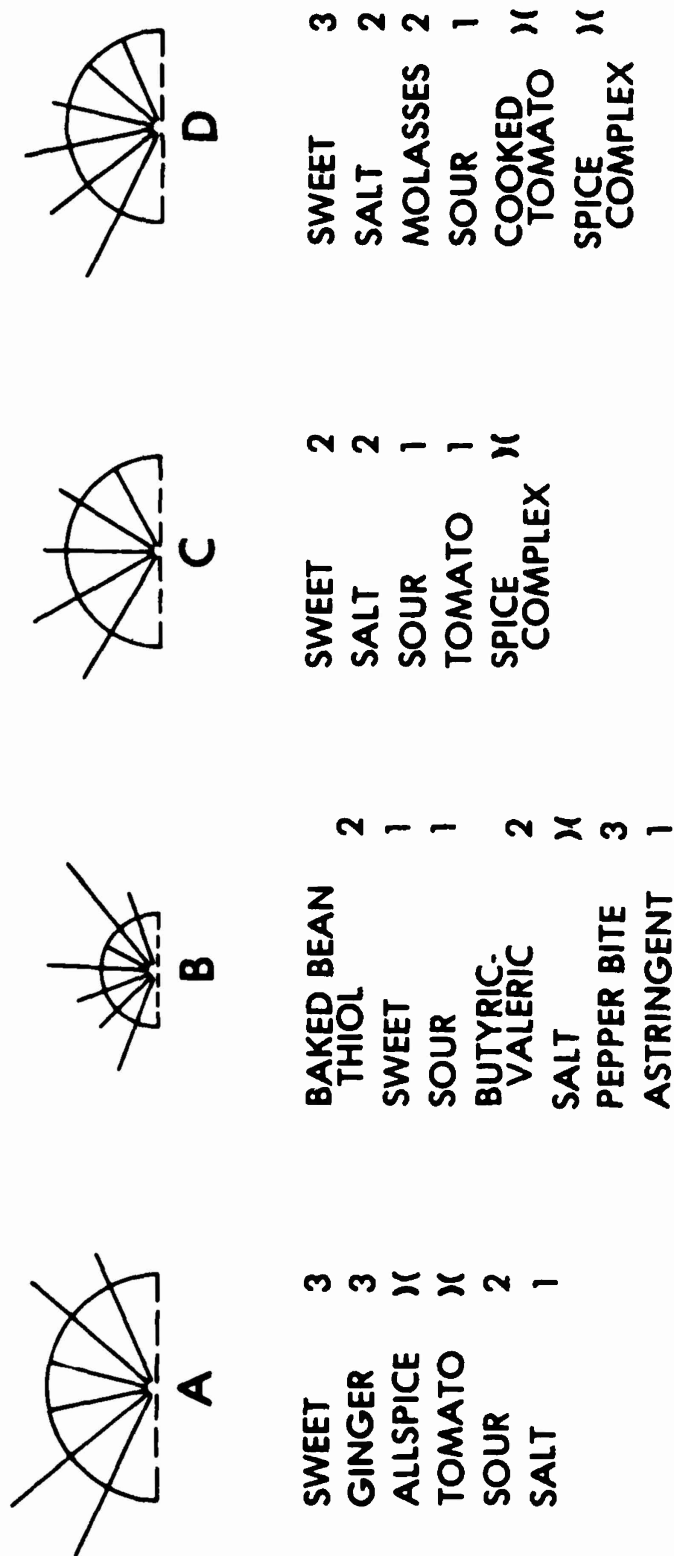
Figure 6. Typical representation of flavor profile data for four commercial catsups.[197]

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B. Descriptive Texture Analysis

A similar profiling approach to the Arthur D. Little Flavor Profile has been developed for the evaluation of food texture at General Foods Corps.[200-203] Although patterned after the flavor profile method, the approach differs from it in several important ways. As mentioned previously, the texture profile method is an attempt to standardize terminology by providing operational definitions for textural attributes. The texture attributes developed for use with the method appear in Table 2. If additional terms are required to describe a complex product, the panel identifies and operationally defines these attributes and includes them in the profile evaluation for that product. The following are definitions that have been developed for the mechanical attributes listed in Table. 2.

Hardness:	Force required to compress a substance between molar teeth (in the case of solids) or between tongue and palate (in the case of semi-solids).
Viscosity:	Force required to draw a liquid from a spoon over the tongue.
Adhesiveness:	Force required to remove the material that adheres to the mouth (generally the palate) during the normal eating process.
Fracturability:	Force with which a sample crumbles, cracks or shatters.
Chewiness:	Length of time (in sec) required to masticate the sample, at a constant rate of force application, to reduce it to a consistency suitable for swallowing.
Gumminess:	Denseness that persists throughout mastication; energy required to disintegrate a semi-solid food to a state ready for swallowing.

[200]A.S. Szczesniak. Classification of textural characteristics. J. Food Sci., 28, 385 (1963).

[201]M.A. Brandt, E.Z. Skinner, and J.A. Coleman. Texture profile method. J. Food Sci., 28, 404 (1963).

[202]G.V Civille and I.H. Liska. Modifications and applications to foods of the General Foods Sensory texture profile technique. J. Texture Stud., 6, 19 (1975).

[203]G.V. Civille and A.S. Szczesniak. Guidelines to training a texture profile panel. J. Texture Stud., 4, 204 (1973).

For each of the attributes defined above, standard scales (ordered series of food products that represent varying degrees of the attribute) have been developed.[201] Using these scales, good correlations were demonstrated between sensory and instrumental (General Foods texturometer and viscosimeter) measures of the texture attributes.[204] These scales help familiarize the panel trainee with the attributes as they exist in real foods. While all items on the standard scales are numbered to represent approximately equal perceptual intervals on the attribute, scaling of test products is carried out using the scalar methods associated with the Arthur D. Little Flavor Profile Method (see section above).

Figure 7 shows a typical texture profile for restructured beef products.[205] These data are for five different formulations of restructured beef. The textural characteristics used to profile the products appear at the bottom of the profile. They include many of the standard texture attributes, as well as some specifically defined for flaked and formed beef. The intensity of each attribute was scaled using the method of magnitude estimation (see next section). This method enabled assignment of a constant value (10.0) to a control sample of whole-muscle meat, allowing easy visual comparison of the restructured products to the control sample.

C.   Descriptive Analysis for Specific Commodities

In addition to the flavor and texture profile methods, many food commodities have evolved their own well-defined set of descriptive terms that are used by highly experienced technical panels operating within that commodity area. For some commodities these sensory attributes can be found in published lists, such as those used for judging beer flavor[206] or dairy products.[207] A comprehensive list of descriptive sensory terms, applying to perfumes and pharmaceuticals, as well as to foods and beverages, is currently

[204]A.S. Szczesniak, M.A. Brandt, and H.H. Friedman. Development of Standard rating scales for mechanical parameters of texture and correlation between the objective and the sensory methods of texture evaluation. J. Food Sci., 28, 397 (1963).

[205]A.V. Cardello, R. Segars, J. Secrist, J. Smith, and R. Rosenkrans. Sensory and instrumental texture properties of flaked and formed beef. Food Microstructure, 2, 119 (1983).

[206]J.F. Clapperton, C.E. Dalgiesh, and M. Meilgaard. Appendix A - Systematic beer flavor terminology. In The Practical Brewer. H. Broderick (ed). Milwaukee, WI: Master Brewers Association of the Americas, 1977, 433.

[207]J.A. Nelson and G.M. Trout. Judging Dairy Products, 5th ed. Milwaukee, WI: Olson Publishing Co., 1964.

Figure 7. Texture profile of restructured beef products containing various ingredients and compared to a control sample of rib-eye steak.

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being complied by Committee E-18 of the American Society for Testing and Materials. Also, ASTM has published a manual[208] on the general sensory evaluation of the appearance of materials (including foods) that could be consulted by the investigator interested in the applied study of the appearance of foodstuffs.

IV. THE QUANTIFICATION OF SENSORY DATA: BASIC RESEARCH AND THEORY

As stated in the Introduction, the first task in developing subjective-objective correlations is to describe qualitatively the important sensory characteristics of the products. Once this has been accomplished, the second task is to measure quantitatively the degree to which the product possesses these attributes. Although products may be described as sweet, chewy or gamey, products vary in the amount of sweetness, chewiness or gaminess. The measurement of the intensity of sensations has formed the heart of the field of psychophysics for the past century, and an understanding of the techniques of sensory measurement must necessarily begin with early research in the area.

A. Psychophysical Scaling

Equation 1 relates the perceived intensity of a qualitative sensory attribute to the physically measured intensity of the stimulus. The major aim of psychophysics has been to define the exact function (f) that relates (perceived intensity) to (physical intensity). Accurate determination of this function would permit prediction of a psychological response (Ψ) from a physical measurement (ϕ) and is the basic goal of all subjective-objective research in the food industry.

Over the past century, two forms of the "psychophysical function" have been proposed. The first was proposed in 1850 by Fechner,[3] who held that sensation magnitude increases as a logarithmic function of stimulus intensity: $\Psi = k \log \phi$. The second was originally proposed by Plateau in 1872, but has been experimentally detailed by Stevens.[209-212] This latter postulate holds that sensation magnitude increases as a power function of stimulus intensity: $\Psi = k \phi^n$.

[208]A.S.T.M. Sensory Evaluation of Appearance of Materials. Philadelphia, PA: American Society for Testing Materials, 1973.

[209]S.S. Stevens. On the psychophysical law. Psych. Rev., 64, 153 (1957).

[210]S.S. Stevens. To honor Fechner and repeal his law. Science, 133, 80 (1961).

[211]S.S. Stevens. The psychophysics of sensory function. In Sensory Communication. W.A. Rosenblith (ed). Cambridge, MA: M.I.T. Press, 1961.

[212]S.S. Stevens. The surprising simplicity of sensory metrics. Am. Psychol., 17, 29 (1962).

B. Fechner's Law

The starting point of Fechner's contributions in this area derived from earlier work done by the German scientist, Ernst Weber. Fechner had worked with Weber at the University of Leipzig and was aware of the basic relationship that Weber had discovered between the size of the "difference threshold" and the absolute intensity at which it is measured. The relationship, which Fechner later termed Weber's Law, states that the increase in the intensity of a stimulus that is necessary to establish a "just noticeable difference" (j.n.d.). in sensation is a constant fraction of the absolute intensity of the stimulus, or:

$$\frac{\Delta\phi}{\phi} = k \tag{2}$$

where ϕ is the absolute intensity of the stimulus, $\Delta\phi$ is the change in intensity of the stimulus that is necessary for a j.n.d., and k is a constant, between zero and one. Within an applied setting, Equation 2 states that the added concentration of flavorant required to increase the perceived flavor intensity of a lemon pudding depends on the level of flavorant already present in the pudding. The greater the concentration already present, the greater the amount of added-flavorant needed to produce a product that is just perceptably stronger in flavor. Moreover, the ratio of the added flavorant concentration to the initial concentration required to produce this j.n.d. will be constant, regardless of the initial concentration.

Using Equation 2, Fechner felt that he could derive a psychophysical law directly relating the magnitude of sensations to the physical magnitude of the eliciting stimuli. However, in its original form, Weber's Law measured only physical variables, since ϕ and $\Delta\phi$ are physical (objective) measures of the stimulus. In order to establish a function in the form of Equation 1, a **psychological** variable had to be introduced. As history puts it, the solution came to Fechner "as he lay abed on October 22, 1850."[210] His solution was to assume that j.n.d.s of sensation are equal, regardless of the absolute stimulus intensity at which they are determined. This assumption, which was later termed "Fechner's conjecture" by his critics, has been the target of frequent criticism. However, the important aspect of this assumption is that it introduced the necessary psychological variable into the equation. It follows that, if all j.n.d.s ($\Delta\Psi$) are equal, and if a j.n.d. is described by Weber's Law, then:

$$\Delta\Psi = c \frac{\Delta\phi}{\phi} \tag{3}$$

Fechner termed Equation 3 the "fundamental formula," and using it mathematically derived a psychophysical law, showing that the perceived magnitude of a stimulus should increase proportionally to the logarithm of the physical intensity of the stimulus ($\Psi = k \log \phi$). Unfortunately for Fechner's theory, his derivation of Equation 3 suffered from several problems. A description and critique of the derivation can be found in the Appendix for the interested reader.

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In spite of problems associated with the derivation of Fechner's Law, empirical tests of the relationship can be made. One such test that Fechner used involved the "summing of j.n.d.s." In this method the absolute threshold (minimum stimulus intensity necessary to elicit a sensation) is determined by one of the classical threshold methods. This threshold intensity is assigned a sensation value of zero. The stimulus intensity that is just noticeably greater than this threshold intensity is then determined and assigned a sensation value of one (1.0). Likewise, the next perceptibly greater intensity is determined and assigned a sensation value of two (2.0). As each j.n.d. is determined, one sensation unit is added to the total. Thus, each j.n.d. represents an equal unit of sensation, and the sum total of j.n.d.s necessary to reach any stimulus intensity is the sensation value for that stimulus. When these sensation values are plotted against stimulus intensity, as in Figure 8, the resultant function is logarithmic.
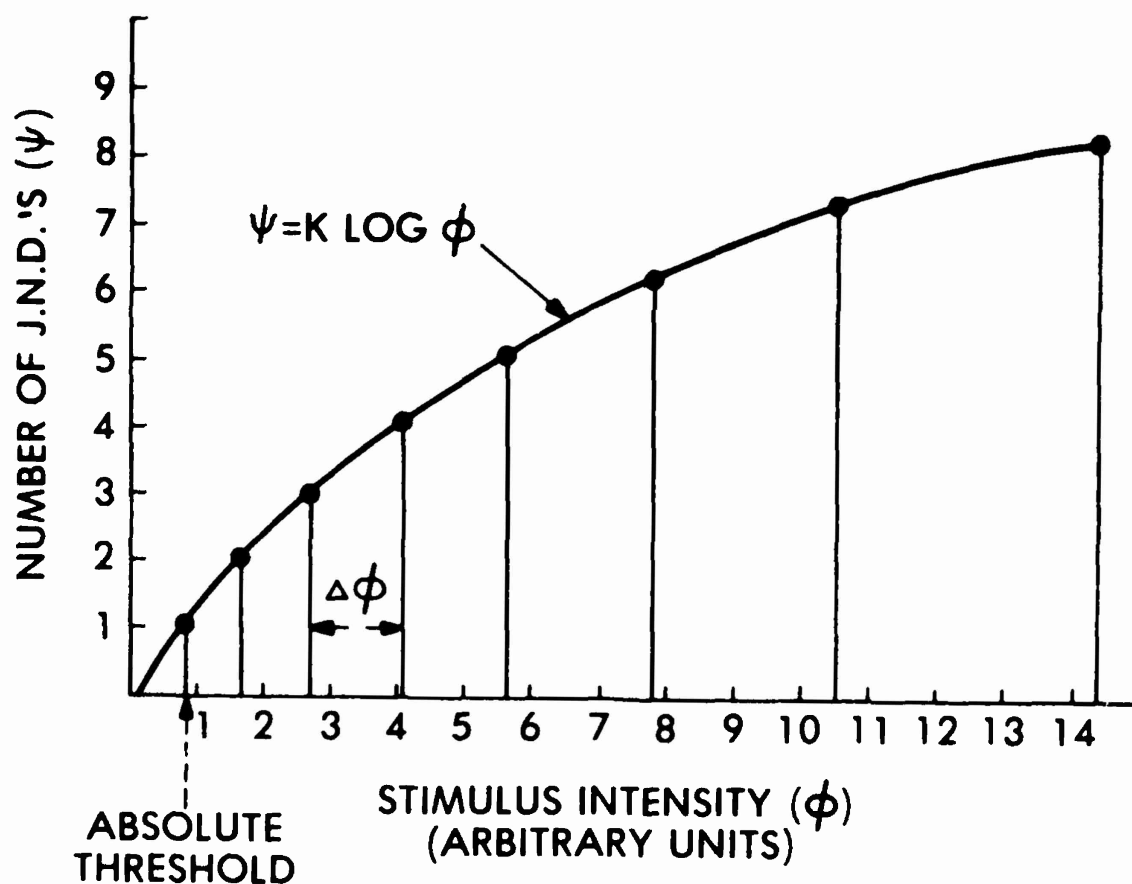
Figure 8. The method os summing j.n.d.s.

Although Fechner's method of "summing j.n.d.s." provided support for his psychophysical law, the method has been openly criticized, because it still directly measures only **physical** or objective variables, i.e., the ϕ's and $\Delta\phi$'s of Weber's Law. At no time are **sensations** directly measured. Rather, the sensation values are assigned by the experimenter with the **assumption** that each j.n.d. is equivalent to one unit of sensation.

Another method that has provided supporting data for Fechner's logarithmic law is that of category scaling. In a category scaling test the panelist is presented with a series of stimuli (foods) that vary along some sensory dimension, such as sweetness. The task of the panelist is to assign each stimulus to one of n equally spaced and numbered categories. (The 9-point hedonic scale, referred to earlier and discussed in more detail in the next section, is a common category scale used in the food industry). The results of numerous studies relating category scale judgments to physical measures of stimuli have shown a logarithmic relationship supporting Fechner's theory (see section that follows for a discussion of how data obtained via category scales compare to data obtained via ratio scales). Nevertheless, the claim that Fechner's methodology is indirect, and therefore without validity, was effectively argued by S.S. Stevens,[210] and led Stevens to propose his own version of the psychophysical law.

C.   Stevens' Law and Ratio Scaling

The most tangible outcome of Fechner's theorizing was the development of a logarithmic scale of sound intensity – the decibel scale. This scale was developed for the convenience of having a measure of physical sound intensity that was proportional to the perceived loudness of the sound. However, as Stevens[213] has pointed out, if Fechner's Law were correct, a tone of 100 dB should sound twice as loud as a tone of 50 dB. In fact, Stevens showed that a tone of 100 dB sounds almost forty times as loud as one of 50 dB.[213] This discrepancy is evidence of a flaw in Fechner's theorizing, and led Stevens to reexamine the relationship between sensory magnitude and physical intensity for all sensory continua.

[213]S.S. Stevens. Neural events and the psychophysical law. Science, 170, 1043 (1970).

51

In his early work, Stevens had enumerated a hierarchy of measurement scales, each defined by the mathematical transformations that leave the scale form invariant.[214] This hierarchy consists of four scale types, proceeding from the simplest scale, called nominal, to ordinal, interval and ratio types. Figure 9 provides examples of each scale. **Nominal** scales are those that merely identify or name objects, without regard for numerical relationships that may exist among them. Examples are the numbers worn by football players and the numbers used to identify television stations. **Ordinal** scales are those that provide information about the rank of each object along some dimension, but provide no information about how close any two objects may be on the underlying dimension. Examples of this type of scale include the numbers assigned to finishing positions for race horses and the academic ranks assigned to graduating college seniors. The third scale type is known as **interval**. These scales provide information about the degree of difference between two or more objects, but the scale has no true zero point. Examples include the Fahrenheit and centigrade scales of temperature. **Ratio** scales are those that possess a true zero point and have the property that the ratios between numbers are meaningful. Examples of this scale type include metric and avoirdupois measures of weight and the Kelvin scale of temperature (40°K means twice as much thermal energy as 20°K; unlike the Fahrenheit and centigrade scales, for which 40°F or $^{\circ}$C does not represent twice as much thermal energy as 20°F or $^{\circ}$C).

Ratio scales afford the greatest amount of information about the relationships among measured objects, and because ratio scales mathematically subsume each of the other scale types, Stevens proposed that only ratio scales were valid for the measurement of sensation. The decision to use ratio scaling led Stevens to the use of "bisection" and "fractionation" methods for scaling intensity. These methods ask the subject to estimate directly the stimulus intensity that appears to be one half (one third, twice, etc.) as loud (sour, flaky etc.) as another stimulus. (A similar form of ratio scaling had been used much earlier by Merkel,[215] but no broad application of the method resulted.) The data obtained from application of these ratio scaling procedures led Stevens to the development of the "sone" scale of loudness.[216]

[214]S.S. Stevens. Mathematics, measurement, and psychophysics. In S.S. Stevens (ed). Handbook of Experimental Psychology. New York: Wiley, 1951.

[215]J. Merkel. Die abhangigkeit zwischen reiz und empfindung. Phil. Stud., 4, 541 (1888).

[216]S.S. Stevens. A scale for the measurement of a psychological magnitude: Loudness. Psychol. Rev., 43, 405 (1936).
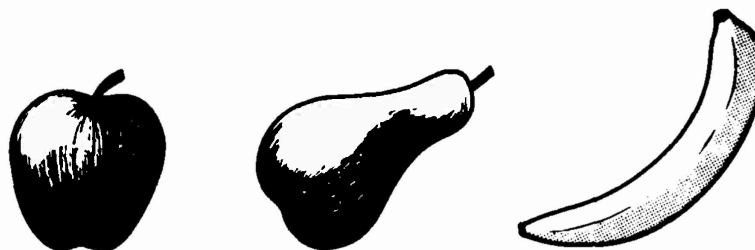
NOMINAL SCALE
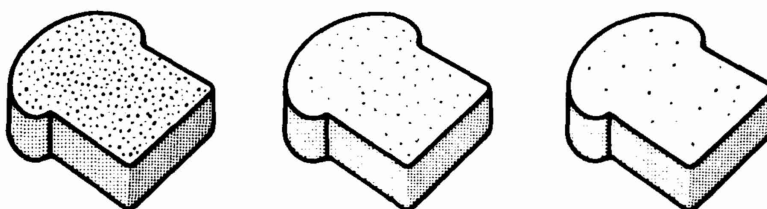
ORDINAL SCALE
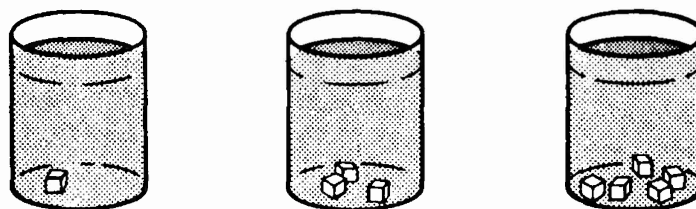
INTERVAL OR CATEGORY SCALE
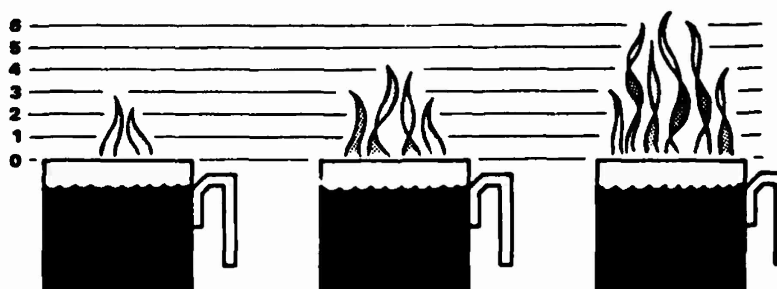
RATIO SCALE

Figure 9. Examples of scale types. In the top example, the three food items are qualitatively different and their names (apples, pear, banana) provide a nominal scale for the food items. In the example of the ordinal scale, three rye breads differ in the number of caraway seeds that they contain; however, since no exact count is available, they are ranked from greatest to least number of seeds. In the next example unit amounts of sucrose are added to three beverages, so that succeeding beverages have intervals of two units. Lastly, two volatiles from three cups of coffee are measured on a gas chromatograph, and it is established that the first cup contains 3/4 the volatiles of the second cup and only 1/2 the volatiles of the third cup.

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The latter scale is nonlinearly related to the decibel scale and reveals a power function relationship between subjective loudness and objective sound intensity.

Inspired by his success, Stevens began the development of other direct ratio scaling methods. In 1953, during a coffee break at the Harvard Psychoacoustics Laboratory, a colleague commented that Stevens treated his subjects as though they had a built-in loudness scale from which they could read off values, as if from an instrument. This simple concept led Stevens to the development of a ratio method in which subjects were allowed to assign their own internal numbers to represent the magnitude of their sensations. Stevens named this method "magnitude estimation."[217] This method has since grown in popularity to where it has now become the most commonly used scaling technique of sensory scientists.

Stevens' main contention, that sensation magnitude grows as a power function of stimulus intensity,[209] can be expressed mathematically as:

$$\Psi = c \, \phi^n \tag{4}$$

where is the magnitude of the sensation, is the intensity of the stimulus, n is the exponent of the power function, and c is a constant of proportionality. The exponent of the power function is an index of the rate of growth of perceived intensity as a function of physical intensity. It is believed to be an invariant characteristic of the sensory attribute being measured and is directly related to the mechanism of energy transduction at the receptor.[213] Figure 10 shows three power functions, each plotted in linear coordinates (left) and in full logarithmic coordinates (right). Plotting the data in full logarithmic coordinates produces a straight line for each function. The reason for this is that when you take the logarithm of both sides of Equation 4. you get $\log \Psi = n \log \phi + \log c$, which is in the form of a function for a straight line, with n (the exponent) being the slope of the line.

[217]S.S. Stevens. Notes for a life story: S.S. Stevens, Notes assembled for a volume of History of Psychology in Autobiography, 1970.

54
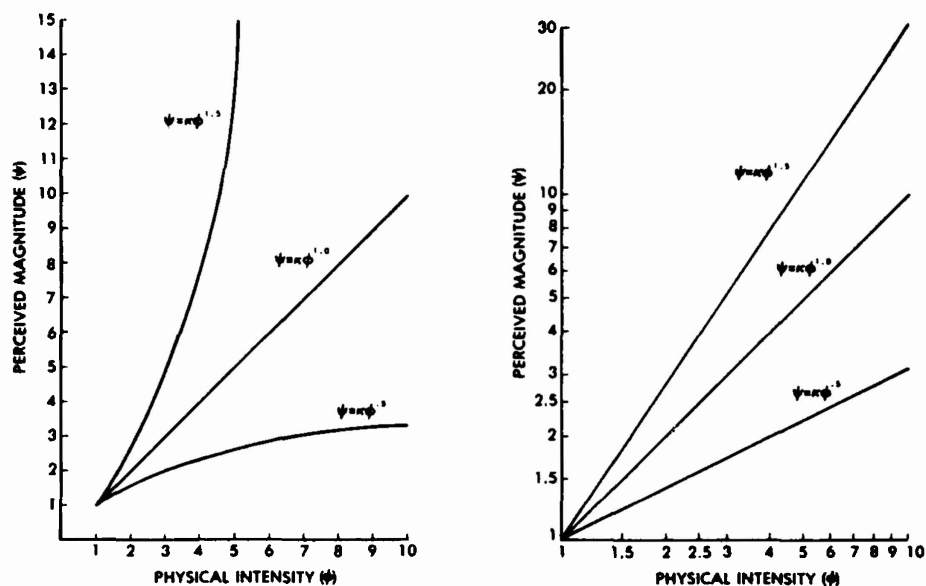
FIGURE 10

Figure 10. Plots of three different power functions in linear (a) and
full logarithmic (b) coordinates.

Table 3 lists some typical exponents that have been found for a variety of
sensory attributes. It is of some note that the exponent for visual line length
is 1.0. This value indicates that perceived length increases proportionately
with actual length. This fact has led to the common use of line scales for
rating sensory intensity[218,219] to avoid problems associated with the use of
numbers, as is discusssed below.

While the exponents in Table 3 are representative, various procedural
factors can affect the size of the exponents obtained by magnitude estimation.
Foremost among these are: (1) the range and spacing of stimuli, (2) the
intensity of the reference stimulus and (3) the value of the modulus (number
assigned to the reference stimulus). Concerning the range and spacing of

[218] J.H.A. Kroeze. Exponential values of the psychophysical power function for
sucrose obtained by two different estimation methods. Chem. Senses & Flavor, 2,
39 (1976).

[219] M.A. Einstein. Use of linear rating scales for the evaluation of beef flavor
by consumers. J. Food Sci., 41, 383 (1976).

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Table 3. Representative exponents of power functions for a variety of sensory attributes

Attribute	Exponent	Stimulus
Bitter Taste	0.65	quinine, sipped
Bitter Taste	0.32	quinine, flowed
Brightness	0.33	5° field
Cold	1.00	metal on arm
Duration	1.10	white noise
Electric Shock	3.50	current through fingers
Hardness	0.80	squeezed rubber
Heaviness	1.45	lifted weights
Lightness (visual)	1.20	gray papers
Loudness	0.67	1000 Hz tone
Salt Taste	1.40	NaCl, sipped
Salt Taste	0.78	NaCl, flowed
Smell	0.55	coffee
Smell	0.60	heptane
Sour Taste	1.00	HCl, sipped
Sweet Taste	1.33	sucrose, sipped
Tactual Roughness	1.50	emery cloths
Thermal Pain	1.00	radiant heat on skin
Vibration	0.95	60 Hz on finger
Vibration	0.60	250 Hz on finger
Viscosity	0.42	stirring fluids
Visual Area	0.70	projected squares
Visual Length	1.00	projected line
Warmth	1.60	metal on arm

stimuli, it has been shown that a smaller range of stimulus intensities will produce a greater exponent[220-226] and that closer spacing of stimuli in one part of the range will produce a local steepening (increase in exponent) for a portion of the function.[225,227-229] Both of these effects appear to be due to the subject spreading a constant range of numbers across a variable range of stimulus intensities. The effect of the intensity of the standard is to produce a lower exponent when the standard stimulus is taken from either extreme of the stimulus range.[220,225,227,230,231] Finally, the number

[220]T. Engen. An evaluation of a method for developing ratio-scales. Am. J. Psychol., 69, 92 (1956).

[221]T. Engen and N. Levy. The influence of context on constant-sum loudness judgments. Am. J. Psychol., 71, 731 (1958).

[222]F.N. Jones and M.J. Woskow. Some effects of context on the slope in magnitude estimation. J. Exp. Psychol., 71, 170 (1966).

[223]E.C. Poulton. The new psychophysics: Six models of magnitude estimation. Psych. Bull., 69, 1 (1968).

[224]S.S. Stevens. The direct estimation of sensory magnitude-loudness. Am. J. Psychol., 67, 1 (1956).

[225]J. Beck and W.A. Shaw. Magnitude of the standard, numerical values of the standard, and stimulus spacing in the estimation of loudness. Percept. & Motor Skills, 21, 151 (1965).

[226]R. Teghtsoonian. Range effects in psychophysical scaling and a revision of Stevens' Law. Am. J. Psychol., 6, 3 (1973).

[227]P.L. Pradhan and P.J. Hoffman. Effect of spacing and range of stimuli on magnitude estimation. J. Exp. Psychol., 66, 533 (1963).

[228]S.S. Stevens. Problems and methods of psychophysics. Psych. Bull., 55, 171 (1958).

[229]R.P. Hellman and J.J. Zwislocki. Some factors affecting the estimation of loudness. J. Acoust. Soc. Am., 33, 687 (1961).

[230]J.C. Stevens and E. Tulving. Estimations of loudness by a group of untrained observers. Am. J. Psychol., 70, 600 (1957).

[231]J. Beck and W. A. Shaw. Magnitude estimations of pitch. J. Acoust. Soc. Am., 34, 92 (1962).

assigned to the modulus by the experimenter,[225,227,230,232] as well as the
number assigned to the first stimulus by the subject during modulus-free
magnitude estimation[231] have been shown to affect the obtained exponent, with
smaller numbers producing larger exponents.

In defense of Stevens' notion of exponent invariance, it should be noted
that many of the above effects, although robust, are small. In addition,
various procedural techniques have been developed to counter these effects.[233]
However, more damaging to Stevens' theorizing are the reports that power law
exponents differ among individuals.[234-238] Such reports have led several

[232]T. Engen and B.M. Ross. Effect of reference number on magnitude
estimation. Percept. and Psychophys., 74 (1966).

[233]S.S. Stevens. Psychophysics: Introduction to its Perceptual, Neural and
Social Prospects. New York: Wiley, 1975, 268.

[234]F.N. Jones and M.J. Marcus. The subject effect in judgments of subjective
magnitude. J. Exp. Psychol., 61, 40 (1961).

[235]M.J. Mitchell and R.A.M. Gregson. Between-subject variation and within-
subject consistency of olfactory intensity scaling. J. Exp. Psychol., 89, 314
(1971).

[236]R.G. Wanschura and W.E. Dawson. Regression effect and individual power
functions over sessions. J. Exp. Psychol., 102, 806 (1974).

[237]W.J. McGill. The slope of the loudness function: A puzzle. In H.R.
Moskowitz, B. Scharf, and J.C. Stevens (eds). Sensation and Measurement.
Boston, MA: Reidel, 1974.

[238]A.W. Lougue. Individual differences in magnitude estimation of loudness.
Percept. and Psychophys., 19, 279 (1976).

investigators[239-250] to conclude that the exponents obtained via magnitude estimation are, in part, determined by the subject's idiosyncratic use of numbers. Stevens[251] has countered this argument with data from experiments on cross-modal matching of intensities, which do not require subjects to make numerical judgments. The basic notion here is that if magnitude estimates of the perceived intensity of one attribute, such as the sourness of acid solutions, are governed by the function

$$\Psi_s = k_s \, \phi_s^{\,n_s} \tag{5}$$

[239] S.J. Rule. Equal discriminability scale of number. J. Exp. Psychol., 79, 35 (1969).

[240] S.J. Rule. Discriminability scales of number for multiple and fractional estimates. Acta Psychol., 35, 328 (1971).

[241] S.J. Rule. Comparisons of intervals between subjective numbers. Percept. and Psychophys., 11, 97 (1972).

[242] S.J. Rule, D.W. Curtis, and R.P. Markley. Input and output transformations from magnitude estimation. J. Exp. Psychol., 86, 343 (1970).

[243] S.J. Rule and D.W. Curtis. Conjoint scaling of subjective number and weight. J. Exp. Psychol., 97, 305 (1973).

[244] W.R. Garner. Advantages of the discriminability criterion for a loudness scale. J. Acoust. Soc. Am., 38, 1005 (1958).

[245] F. Attneave. Perception and related areas. In Psychology: A Study of Science, Vol. 4. S. Koch (ed). New York: McGraw-Hill, 1962.

[246] D.M. MacKay. Psychophysics of perceived intensity: A theoretical basis for Fechner's and Stevens' laws. Science, 139, 1213 (1963).

[247] G. Ekman. Is the power law a special case of Fechner's law? Percept. & Motor Skills, 19, 730 (1964).

[248] M. Treisman. Sensory scaling and the psychophysical law. Quarterly J. Exp. Psychol., 16, 11 (1964).

[249] M. Treisman. What do sensory scales measure? Quart. J. Exp. Psychol., 16, 387 (1964).

[250] B. Schneider, S. Parker, D. Ostrosky, D. Stein, and G. Kanow. A scale for the psychological magnitude of number. Percept. & Psychophys., 16, 43 (1974).

[251] S.S. Stevens. On the operation known as judgment. Am. Sci., 54, 385 (1966).

and magnitude estimates of the perceived intensity of another attribute, such as the loudness of 1000 Hz tones, are governed by the function

$$\Psi_l = k_l \, \phi_l^{\,n_l} \tag{6}$$

then by matching the perceived loudness (Ψ_l) of a 100 Hz tone to equal the perceived sourness (Ψ_s) of an acid solution, one can set the two equations equal to one another, to obtain

$$k_l \, \phi_l^{\,n_l} = k_s \, \phi_s^{\,n_s} \tag{7}$$

or

$$\phi_l = (\frac{k_s}{k_l})^{1/n_l} \, \phi_s^{\,(n_s/n_l)} \tag{8}$$

The function obtained by relating the physical loudness of tones (ϕ_l) to match various physical concentrations of acid solutions (ϕ_s) is a power function, and the exponent of the function is equal to the ratio of the original exponents. Numerous studies[252-262] in which such cross modal

[252] S.S. Stevens. On predicting exponents for cross-modality matches. Percept. & Psychophys., 6, 251 (1969).

[253] S.S. Stevens. Tactile vibration: Change of exponent with frequency. Percept. & Psychophys., 3, 223 (1968).

[254] D.W. Panek and S.S. Stevens. Saturation of red: A prothetic continuum. Percept. & Psychophys., 1, 59 (1966).

[255] B. Bond and S.S. Stevens. Cross-modality matching of brightness to loudness by 5-year olds. Percept. & Psychophys., 6, 337 (1969).

[256] H.R. Moskowitz. Scales of intensity for single and compound tastes, doctoral dissertation. Cambridge, MA: Harvard University, 1969.

[257] S.S. Stevens. Matching functions between hardness and ten other continua. Percept. & Psychophys., 1, 5 (1966).

[258] L.E. Marks and L.M. Bartoshuk. Ratio scaling of taste intensity by a matching procedure. Percept. & Psychophys., 26, 335 (1977).

[259] L.E. Marks. Sensory Processes: The New Psychophysics. New York: Academic Press, 1974, 270.

[260] J.C. Stevens and L.E. Marks. Cross-modality matching of brightness and loudness. Proc. Nat. Sci., 54, 407 (1965).

[261] S.S. Stevens and M. Guirao. Subjective scaling of length and area and the matching of length to loudness and brightness. J. Exp. Psychol., 66, 177 (1963).

[262] S.S. Stevens. Cross-modality validation of subjective scales for loudness, vibration, and electric shock. J. Exp. Psychol., 57, 201 (1959).

matchings have been conducted have confirmed the above predictions. This impressive transitivity in power function exponents led Stevens[251] to the generalization that magnitude estimation is itself a cross-modal procedure in which numbers are matched to sensations.

D. Ratio Scales vs. Category Scales

With the advent of ratio scaling techniques, such as magnitude estimation, the question was asked as to how the data obtained via these methods compared with data obtained via interval scaling techniques, such as category scaling. In a series of studies[263] addressing this question it was shown that category scales produce data that are concave downward relative to ratio scales on continua such as brightness, loudness and sweetness, while on other continua, such as tonal pitch and hue, category scales produce data that are linearly related to ratio scales. This difference led researchers to distinguish between two types of sensory continua – prothetic and metathetic.[263] Prothetic continua, such as brightness, loudness and sweetness, are defined as those "for which discrimination appears to be based on an additive mechanism by which excitation is added to excitation at the physiological level," while metathetic continua, such as tonal pitch and hue, are defined as those "for which discrimination behaves as though based on a substitutive mechanism at the physiological level."[263] Metathetic continua may be thought of as those in which sensations differ qualitatively, rather than quantitatively. Stevens argued that the chief factor resulting in the nonlinearity of the scales for prothetic (quantitative) continua is discrimination bias, caused by the subject's variation in sensitivity to differences.[209] Because people discriminate better at the lower end of the continuum than at the higher end, the ability to distinguish one magnitude from another varies over the stimulus range and affects the width of categories. Since sensations on metathetic continua differ qualitatively, this bias is not present, and, therefore, the category scale is linearly related to the ratio scale.

Most of the continua of interest to the food industry are prothetic; therefore, one should consider the relative validity of the two types of scales before making a choice to use one or the other.

E. Validity of Scales

The question of the validity of scales of sensation is a thorny one and has led at least one author to conclude that "no one scale, however carefully

[263]S.S. Stevens and E.H. Galanter. Ratio scales and category scales for a dozen perceptual continua. J. Exp. Psychol., 54, 377 (1957).

established, can be considered better than other scales obtained under different conditions of judging."[264] Nevertheless, various theoretical and empirical data bear on the question of the relative validity of ratio and category scales.

First, the internal consistency of ratio scale data is supported by the results of cross-modal matching experiments, as mentioned previously. Second, certain eletrophysiological measures of sensory functioning support the power law. In particular, although electrical recordings from the peripheral nerves of infrahuman mammalian species have revealed a variety of stimulus-response functions, including linear, logarithmic, power and sigmoid functions (see Rosner and Goff[265] and Lipetz[266]), recordings from peripheral and central nervous system areas in humans have frequently demonstrated a power function relationship between stimulus and response. The latter studies include reports that the amplitude of slow components of cortical brain waves are power functions of stimulus intensity for tones, electric current and vibration,[267,268] and that the cortical evoked response to flashes of light,[269] to electrical stimulation of the tongue,[270] to electrical shock to

[264]H. Helson. Adaptation-Level Theory: An Experimental and Systematic Approach to Behavior. New York: Harper & Row, 1964.

[265]B. Rosner and W. Goff. Electrical responses of the nervous system and subjective scales of intensity. In Contributions in Sensory Physiology, Vol. 2. New York: Academic Press, 1967.

[266]L. Lipetz. The relation of physiological and psychological aspects of sensory intensity. In Handbook of Sensory Physiology, Vol. 1, W.R. Lowenstein (ed). New York: Springer-Verlag, 1971.

[267]W.D. Keidel and M. Spring. Neurophysiological evidence for the Stevens power function in man. J. Acoust. Soc. Am., 38, 191 (1965).

[268]K. Ehrenberger, P. Finkenzeller, W.D. Keidel, and K. Plattig. Elektrophysiologische korrelation der Stevenschen potenzfunktion und objektive schwellenmessung am vibrationssinn des menschen. Pfluegers Arch. Gesamte. Physiol. Menschen Tiere. 290, 114 (1966).

[269]V. Loewenich and P. Finkenzeller. Reizstorkeabhangigkeit und Stevenesche potenzfunktion beim optisch evozierten potential des menschen. Pfluegers Arch. Gesamte Physiol. Menschen Tiere, 293, 256 (1967).

[270]K.H. Plattig. Subjective schwellen-und intensitatsabhangig-keitsmessungen am elektrischen geschmack. Pfluegers Arch. Gesamte Physiol. Menschen Tiere, 294, 76 (1967).

the skin [271] and to tactile stimulation of the fingers[272] are all power functions of stimulus intensity.

Although the above reports provide data that Steven's power law has physiological validity, the most important physiological confirmation of this law in humans was provided by a team of Swedish researchers. These investigators[273,274] recorded the summated neural response in the chorda tympani nerve (taste nerve) of patients undergoing inner ear operations. Magnitude estimates of the intensity of the same taste stimuli as were used in this experiment had been obtained from the patients on previous days. The magnitude estimates of the perceived intensity of solutions of sodium chloride, sucrose and acid were all well-described by power functions and the neural data were found to be proportional to the magnitude estimates.[275]

As a final comment on the theoretical aspects of scaling intensity, the past decade has also seen considerable emphasis placed on "functional" measurement, an approach which attempts to solve the problem of psychophysical scaling by simultaneously analyzing the stimulus, the response, and the

[271]H. Davis, C. Bowers, and E. Hirsch. Relations of the human vertex potential to acoustic input: Loudness and masking. J. Acoust. Soc. Am., 43,

[272]O. Franzen and K. Offenloch. Evoked response correlates of psychophysical magnitude estimates for tactile stimulation in man. Exp. Brain Res., 8 (1969).

[273]G. Borg, H. Diamant, L. Strom, and Y. Zotterman. A comparative study of neural and psychophysical responses to gustatory stimuli. In Second Symposium on Olfaction and Taste. T. Hayashi. Oxford: Pergamon Press, 1967.

[274]G. Borg, H. Diamant, L. Strom, and Y. Zotterman. The relation between neural and perceptual intensity: A comparative study on the neural and psychophysical response to taste stimuli. J. Physiol., 192, 13 (1967).

[275]Y. Zotterman. The recording of the electrical response from human taste nerves. In Handbook of Sensory Physiology, Vol. 4. L. Beidler (ed). New York: Springer-Verlag, 1971, 102.

cognitive or judgmental process relating the two.[276-279] Using factorial approaches, several impressive tests of this model have been made.[280-283]

For those who prefer practical over theoretical considerations, a compelling list of the practical advantages of ratio scaling over other procedures may allay doubts concerning the use of these methods. These advantages include:

1. The ability to express the perceived intensities of samples as ratios or proportions, i.e., sample X is two thirds as chewy as sample Y.

2. There are no end-points on the scales, so panelists cannot run out of numbers to assign to extreme samples.

3. The scales are continuous, thereby allowing discrimination accuracy to be equal to that of the perceptual system.

4. The scales are simple to use, and can be easily adapted for use with children[284-255] and other populations who may have difficulty in making numeric judgments. e.g.. cross-modal matching.

[276]N.H. Anderson.   Application of an additive model to impression formation. Science, 138, 817 (1962).

[277]N.H. Anderson.   On the quantification of Miller's conflict theory. Psychol. Rev., 69. 400 (1962).

[278]N.H. Anderson.   Functional measurement and psychophysical judgment. Psychol. Rev., 77, 153 (1970).

[279]N.H. Anderson.   Algebraic rules in psychological measurement. Am. Sci., 6⁻. 555 (1979).

[280]N.H. Anderson.   Note on functional measurement and data analysis.   Percept. & Psychophys.. 21, 201 (1977).

[281]N.H. Anderson.   Cross-task validation of functional measurement.   Percept. & Psychophys., 12, 389 (1972).

[282]N.H. Anderson.   Weak inference with linear models.   Psych. Bull., 84, 1155 (1977).

[283]R.S. Bogartz.   Some functional measurement procedures for determining the psychophysical law. Percept. & Psychophys., 27, 284 (1980).

[284]D.D. Dorfman and R. Megling.   Comparison of magnitude estimation of loudness in children and adults. Percept. & Psychophys., 1, 239 (1966).

5. After normalization, the data can be analyzed using parametric statistics. (Note, however, recent discussions of this point.[285-288])

6. For the purposes of studying subjective-objective correlations, the method provides ratio scale data to match the ratio scale data provided by most instrumental measurements.

V. THE QUANTIFICATION OF SENSORY DATA: APPLICATIONS

The section that follows describes the practical use of common scaling techniques in the evaluation of food products. The methods and tests are organized according to scale type, i.e., nominal, ordinal, interval and ratio, and one or more detailed examples of the use of the methods are presented. Although the methods and tests that are covered are not exhaustive (numerous variations exist for each technique), the examples are representative of the general class of tests in each category.

A. Nominal Scaling

Nominal scales, as stated previously, merely identify or name different objects or classes of objects. The numbers assigned to these objects serve only as labels and can be substituted in a one-to-one manner for any other set of numbers (or other identifying symbols) without loss of the scale information. In the food industry, the most commonly used nominal tests are **difference tests.**

As a class, difference tests aim to identify samples that differ along some sensory attribute. Such tests are classified according to the number of samples presented and the order of presentation of samples. In some cases, only a single sample is presented. These "single-sample" tests require the panelist to compare the sample to an internal standard and to classify the

[285]F.M. Lord. On the statistical treatment of football numbers. Am. Psychol., 8, 750 (1953).

[286]J. Gaito. Scale classification and statistics. Psychol. Rev., 67, 277 (1960).

[287]C.A. Boneau. A note on measurement scales and statistical tests. Am. Psychol., 16, 260 (1961).

[288]J. Gaito. Measurement scales and statistics: Resurgence of an old misconception. Psych. Bull., 87, 564 (1980).

sample as the same or different from that internal standard. Two-sample tests are termed "paired-comparison tests" when they are presented simultaneously, or "single-stimulus tests" when they are presented successively. In both cases the task is to indicate whether the samples are the same or different. Three-sample tests are termed "duo-trio tests" if they are presented successively and "triangle tests" if they are presented simultaneously. In a duo-trio test, a standard is presented first, followed by a pair of samples, and the task is to identify the sample that is the same as the standard. In a triangle test, all three samples are presented together and the panelist must identify the odd sample. Tests with greater than three samples are termed "multisample tests," and require sorting of the samples into two or more categories.

Example: The following is a typical example of a difference test, using data taken from our laboratory. In this example, a triangle test was conducted to determine whether a significant difference existed between restructured beef steaks comminuted with two different blade sizes. Cooked samples, prepared and administered using standard sensory testing procedures, were presented to a total of 16 panelists. Each panelist was presented with three samples. Of these three samples, two were comminuted with one blade size and one was comminuted with a different blade size. The "odd" sample was balanced among panelists, and the order of all samples was randomized. Panelists were asked to identify the one sample of the three that was different.

Of the 16 panelists in the test, 12 correctly identified the odd sample. The probability of obtaining 12 correct identifications by chance can be calculated using the binominal expansion, or by reference to tables that have been developed for this purpose. It was ascertained that the probability of 12 correct identifications by chance is less than 0.1%. It was concluded that the two blade sizes produce products that are significantly different from one another.

Note that the only conclusion that one can draw from the above test, or any other simple difference test, is that the samples are the same or different. If they are different, as in this case, nothing can be concluded about which sample has more or less a given sensory attribute. Such conclusions require the use of ordinal scaling techniques.

B.   Ordinal Scaling

Ordinal scales are those that provide information about the order or rank of objects along some sensory dimension. The most commonly used ordinal methods for evaluation of foods are those of **directional difference testing** and **ranking**. While directional difference tests are similar to simple difference tests in many respects, the distinguishing characteristic is that they require the panelist to judge which of two samples possesses **more** or **less** of a given sensory attribute.

Example: An example of a "directional paired-comparison test" might involve a confectioner who wishes to reduce the amount of sugar in his

formulation for vanilla fudge. He is concerned with whether this reduction in sugar will result in a significant reduction in the perceived sweetness of the fudge. In a directional paired-comparison test, each of the two samples of fudge (the old and new formulations) would be presented simultaneously to panelists. Panelists would be asked to either identify the sample that was less sweet or the sample that was more sweet. It is important, of course, that other sensory aspects of the samples, e.g. color, be identical so that judgments of sweetness intensity are not confounded by other differences between the samples.

The obtained data can then be tested statistically, using similar techniques as used for standard difference tests (binomial expansion, X^2 tests). If a significant difference is found, it can be concluded that the new formulation of fudge is, in fact, less sweet than the old formulation. Of course, no information is provided concerning how much less sweet it is. To answer this question requires the use of interval scaling techniques. A complete review of directional and nondirectional difference tests can be found in the text by Amerine, Pangborn, and Roessler.[4]

The major difference between directional difference tests and ranking tests is the number of samples that are ordered. All of the directional difference tests establish an ordinal relationship for only two samples, while ranking procedures allow ordinal scaling of more than two samples. In ranking tests, panelists are asked to order a series of samples along some sensory dimension. For example, if a fish processor wants to assess the effect of storage temperature on the freshness of fish samples, he/she might have a sensory panel conduct a ranking test in which samples stored at five different chill temperatures are evaluated for degree of triethylanine odor. Each of the five fish samples would be presented simultaneously. Panelists would be asked to evaluate each sample and to arrange them in increasing (or decreasing) order of intensity of odor. Mean ranks for each sample could then be used for Spearman rank-order correlational analyses with the dependent variable. Tests of differences among samples could also be conducted using one of a variety of statistical tests devised for rank-order data.[289-293]

[289]R.A. Bradley and M.E. Terry. Rank analysis of incomplete block designs. I. The method of paired comparisons. Biometrika, 39, 324 (1952).

[290]M.E. Terry, R.A. Bradley, and L.L. Davis. New designs and techniques for organoleptic testing. Food Technol., 6, 250 (1952).

[291]R.G. Steel. A multiple comparison rank sum test: Treatment versus control. Biometrics, 15, 560 (1959).

[292]R.G. Steel. A rank sum test for comparing all pairs of treatments. Technometrics, 2, 197 (1960).

[293]A. Kramer. A rapid method for determining significance of differences from rank sums. Food Technol., 14, 576 (1960).

Although ordinal scales provide information about the order of stimuli along some dimension, it must be remembered that no information is provided about the **degree of difference** among the stimuli. Thus, like nominal scales, ordinal scales provide relatively little information about the quantitative relationships among stimuli.

C.   Interval Scaling

Interval scales are the first scales in the hierarchy of scale types that provide information about the sensory distances or sensory intervals between stimuli. The most widely used interval scale method in sensory evaluation is the category scale. The most common category scale used in the food industry is the nine-point hedonic scale, referred to earlier in the section on hedonic quality.

Category scales may vary in many respects. First of all, each category or point on the scale may have a verbal label, or, alternatively, only the extreme categories may have labels. One problem with labeled scales is that the verbal labels are sometimes chosen intuitively and arbitrarily. Under such circumstances they cannot be considered as equal-interval scales.

Example: As an example, Figure 11 shows the nine-point hedonic scale, which is a typical labeled category scale. Although the scale is assumed to consist of equal intervals, examination of data on the perceived differences between scale labels[209] indicates that the equality of these intervals is a questionable assumption. Also related to the problem of using verbal labels are the suggestions that the "dislike moderately" category is ambiguous, being interpreted differently by different people and that the "neither like nor dislike" category is not essential.[294]
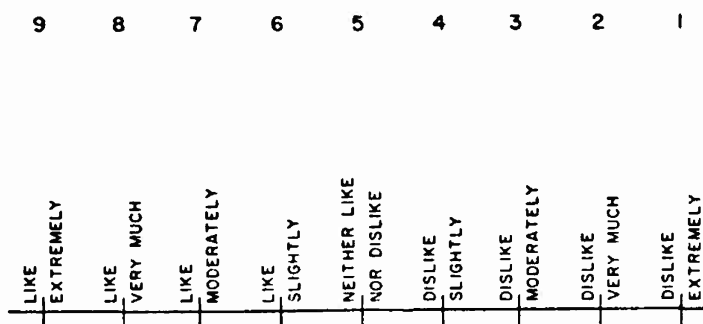
Figure 11.   The nine-point hedonic scale.

[294]L.V. Jones, D.R. Peryam, and L.L. Thurstone. Development of a scale for measuring soldiers' food preferences. Food Res., 20, 512 (1955).

Unlabeled scales do not necessarily avoid the problem of assessing the distances between adjacent categories. For example, in an attempt to address the problems of ambiguity in the interpretation of verbal labels and the fact that verbal labels may be difficult for children to use, facial hedonic scales have been developed.[295] These scales consists of a series of "smiley faces" each of which expresses a different facial smile or frown. Respondents simply check the facial expression that best represents their effective response to the product. Although numerical values can be assigned to each category for the purpose of data analysis, the perceptual distances between categories is unknown. Such a scale can provide ordinal data at best.

Several other disadvantages of interval scales have been reported throughout the years. One is that people tend to avoid use of the extreme categories, thereby distorting the scale. Another is the fact that the upper and lower end-points force panelists to place extremely weak or extremely strong stimuli, that might otherwise be "off the scale," into an artificially restricted set of categories. Still other disadvantages are revealed when the data are compared to ratio scale data, as previously discussed. Even though there are numerous disadvantages associated with interval scaling procedures, they are the most frequently used scale types in the area of sensory evaluaton, due to their simplicity of use and interpretation.

D. Ratio Scaling

One of the major limitations of interval scales is that they do not possess a true zero point. Any constant can be added to the numbers on an interval scale and the interval relationship among the numbers is maintained. For example, if two stimuli are assigned the values 2.0 and 6.0, adding the constant 3.0 to both produces scale values of 5.0 and 9.0. Although the interval is maintained, namely 4.0 units, the ratios between the numbers have changed. In this example, the ratio of the original values is 1/3, while the ratio of the transformed values is 5/9. Thus, it is impossible to determine whether one stimulus is twice, one-half, one-third, etc., as strong as another stimulus while using interval scaling procedures. Statements about **ratios** of stimulus intensity require that a true zero point exists on the scale, a characteristic that is inherent only in ratio scales.

As stated in the previous sections, there are a variety of ratio scaling techniques that can be used to scale sensation. However, the most common technique is magnitude estimation. Several excellent, practical descriptions

[295]B.H. Ellis. A critical review of recent literature on preference testing methodology: Part I. Food Technol., 22, 49 (1968).

of magnitude estimation are available in the literature.[296-298] Because of the importance of this method, a detailed example of magnitude estimation and the analysis of magnitude estimation data are provided.

E.   Magnitude Estimation - A Detailed Example

Problem: A noncarbonated beverage manufacturer produces a variety of fruit drinks varying in sweetness. The sweetening agent the manufacturer is now using in the products is sucrose, but the manufacturer has been approached by a distributor of an alternative sweetener who suggests that the company can substitute the new sweetener in all of the products at the *same formulation level* and produce equally sweet products at reduced cost. In order to assess the distributor's claims, the manufacturer asks the sensory evaluation team to evaluate the new sweetener.

Each of the five fruit drinks made by the manufacturer is prepared using the standard formulation. The sucrose levels in these products are 1.5, 3.0, 5.0, 9.0 and 14.0% wt/wt. Each of these fruit drinks is mixed using the same concentrations of the low-cost sweetener, producing a total of 10 test samples. A consumer test is scheduled to evaluate the samples for sweetness. If the beverages formulated with the new sweetener are either as **sweet** or **sweeter** than the sucrose-formulated beverages, then the new sweetener is acceptable for use.

Although a large-scale consumer test might be planned, for simplicity, our example will be based on 10 panelists. If the consumers are unfamiliar with magnitude estimation, a training session would be scheduled prior to the actual test. Such a training session usually involves a description of the method, as well as practice in using magnitude estimation to judge some simple sensory dimension, such as judging the lengths of lines or the areas of circles. While such training is useful, especially if panelists have been previously exposed to other scaling procedures, it is not mandatory. The procedure of magnitude estimation, as we shall see, is simple enough to be understood by most people with only a simple set of written instructions.

[296]H.R. Moskowitz. Sensory evaluation by magnitude estimation. Food Technol., 28, 16 (1974).

[297]H.R. Moskowitz and D. Fishken. Getting more out of your product by magnitude estimation scaling. Baker's Digest, 53, 28 (1979).

[298]H.R. Moskowitz. Magnitude estimation: Notes on what, how, when, and why to use it. J. Food Qual., 3, 195 (1977).

At the start of the test session, panelists would be provided with a set of written instructions. Typical instructions for the test read as follows:

> Your task in this experiment is to judge the **sweetness** of a series of beverages. You will judge the sweetness of each beverage by assigning a number to it which is proportional to its sweetness. When the first sample is presented you may assign to it any number that you feel is appropriate. All subsequent judgments are to be made in relation to the first, so that the ratio of the sweetness of a given sample to the sweetness of the first sample is the same as the ratio of the numbers assigned to each. For example, if you assign the number 50 to represent the sweetness of the first beverage and the second tastes twice as sweet, you should assign it the number 100; if the second beverage tastes one-half as sweet as the first, then you should assign it the number 25; and so on. You may use whole numbers, decimals or fractions to make your judgments.

The important aspect of the above instructions is the emphasis on making ratio judgments. It should be pointed out that these are designed for "modulus-free" magnitude estimation, i.e., the number assigned to represent the sweetness of the first sample is arbitrary and is left to the panelist. An alternative procedure is for the experimenter to assign an arbitrary number to the first stimulus and to have all panelists use this same number (modulus) as their reference value. The latter technique avoids the need for subsequent mathematical transformations of the data, but the former method is better, since it allows each panelist to use a set of numbers with which he/she is comfortable, rather than constraining the panelist to some artificially imposed range of numbers.

Following instructions, samples are presented to panelists in random order, using all appropriate experimental controls that are normally associated with sensory evaluation tests. Table 4 depicts a typical set of raw data that might be obtained with this procedure.

The first step in analyzing the magnitude estimates is to transform the data, so as to remove the variability that is due to each subject using his own modulus. This "modulus equalization" procedure involves calculation of the geometric mean of the magnitude estimates across all stimuli for each individual panelist. The geometric mean is used, rather than the arithmetic mean, because magnitude estimates have been shown to have an approximately log-normal distribution.[299] (The median may also be used, especially if the data set contains zeroes). The formula to calculate the geometric mean (GM)

[299] J.C. Stevens. A comparison of ratio scales for the loudness of white noise and the brightness of white light, Doctoral Dissertation. Cambridge, MA: Harvard University, 1957.

Table 4. Example of raw data collected by the method of magnitude estimation. Data are judgments of the sweetness of beverages containing various concentrations of sucrose or an alternative sweetener.

Panelist	Sucrose					Alternative Sweetener					PGM	GGM/PGM
	1.5%	3.0%	5.0%	9.0%	14.0%	1.5%	3.0%	5.0%	9.0%	14.0%		
1	1	4.5	6	10	20	0.25	3	4	10	15	4.35	4.299
2	50	100	150	200	300	.50	70	100	100	175	110.67	0.1690
3	2	3	5	7.5	10	1.5	2	2.5	5	8	3.83	4.883
4	1.0	1.25	3.5	9	15	0.5	1.5	3	6	12	3.15	5.937
5	150	550	900	1300	1200	25	75	300	650	1000	365.33	0.0512
6	0.025	0.02	0.15	0.8	0.9	0.05	0.06	0.1	1.0	0.8	0.16	116.9
7	12	100	75	175	250	10	10	15	40	100	43.38	0.4311
8	2	7	14	20	25	1	3.5	10	20	20	8.20	2.280
9	500	1000	5000	10,000	20,000	300	750	2000	8000	15,000	2774.19	0.0067
10	7	10	15	24	36	10	10	16	20	30	15.63	1.196

The column labeled PGM lists the geometric means across all samples for each panelist and the column labeled GGM/PGM is the ratio of the grand geometric mean of all the data divided by each panelist's PGM.

is GM $= (y_1 \cdot y_2 \cdot y_3 \cdot \ldots y_n)^{1/n}$ or the nth-root of the product of n scores. The geometric means for each panelist (PGM) in our example are shown in the next to last column of Table 4. Since these means reflect the average of the numbers used by each panelist, the problem of different moduli can be offset by equating these means to a common value. Several procedures for such modulus equalization are available.[300] In this case, equalization was done by first calculating the geometric mean of the entire set of data (all panelists and all samples). This grand geometric mean (GGM) represents the average of the entire data set, and it is this value to which all panelist means are equated. The latter transformation is achieved by calculating the ratio of the grand geometric mean (GGM) to each panelist mean (PGM) (these panelist ratios appear in the last column of Table 4). Each panelists's raw magnitude estimates are then multiplied by his/her panelist ratio. Table 5 shows the equalized data.

Note that in Table 5 the ratio among ratings for any panelist is the same as before transformation (Panelist #2 assigned the value 50 to the sample containing 1.5% sucrose and the value 100 to the sample containing 3.0% sucrose, a ratio of 1/2). In the transformed data, Panelist #2's rating for 1.5% sucrose is 8.45 and for 3.0% sucrose it is 16.90, still a ratio of 1/2. Thus, the ratios among the data for each panelist have been preserved, and only the absolute scale values have changed. If replicate samples are judged in the same session by the same panelists, the data from all replicates are included in calculating the subject geometric means (PGMs). However, if replicates are conducted on separate days, then panelists' judgements made on different days are treated as if made by different subjects for the purpose of equalization.

Once the raw data have been equalized, measures of central tendency can be calculated and the data plotted. In this case, the geometric mean of the magnitude estimates for each sample beverage is of primary interest. The geometric means for each sample are shown below each column in Table 5. Figure 12 shows these means for the two series of beverages, plotted in full logarithmic coordinates. The fact that both sets of data are well fit by a straight line suggests that the relationship between perceived sweetness and sweetener concentration can be described by a power function. The slope of the straight lines through both sets of data is approximately 1.2. Thus, the exponent of the power function governing the growth of sweetness in this experiment is 1.2.

[300] J.J. Powers, C.B. Warren, and T. Masurat. Collaborative trials involving three methods of normalizing magnitude estimations. Lebensm. Wiss. Technol., 14, 86 (1981).

Table 5. Data from Table 4 "equalized" to remove variability due to different moduli.

Panelist	Sucrose					Alternative Sweetener				
	1.5%	3.0%	5.0%	9.0%	14.0%	1.5%	3.0%	5.0%	9.0%	14.0%
1	4.30	19.35	25.79	42.99	85.98	1.07	12.90	17.20	42.99	64.49
2	8.45	16.90	25.35	33.80	50.70	8.45	11.83	16.90	16.90	29.58
3	9.77	14.65	24.42	36.62	48.83	7.32	9.77	12.21	24.42	39.06
4	5.94	7.42	20.78	53.43	89.06	2.97	8.91	17.81	35.62	71.24
5	7.68	28.16	46.08	66.56	61.44	1.28	3.84	15.36	33.28	51.20
6	2.92	2.34	17.54	93.52	105.21	5.85	7.01	11.36	116.90	93.52
7	5.17	43.11	32.33	75.33	107.78	4.31	4.31	6.47	17.24	43.11
8	4.56	15.96	31.92	45.60	57.00	2.28	7.98	22.80	45.60	45.60
9	3.35	6.70	33.50	67.00	134.00	2.01	5.03	13.40	53.60	100.50
10	8.28	11.96	17.94	28.70	43.06	11.96	11.96	19.14	23.92	35.88
GM	5.62	12.92	26.43	50.91	73.68	3.58	7.71	14.52	34.63	53.16

Each panelist's raw scores have been multiplied the value appearing in the last column of that table. The geometric means (GM) of the equalized judgments calculated for each stimulus appear in the bottom row.

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It can be seen in Figure 12 that the new sweetener produces a lower magnitude of perceived sweetness in all of the sample beverages. However, to test whether these differences are statistically significant, the data in Table 5 must first be converted to logarithms in order to "normalize" the distribution of data. Once this has been done, parametric statistics may be applied to the data. In the above example, a two-way repeated measures analysis of variance can be conducted to assess the effects of the type of sweetener and sweetener concentration on the obtained judgments. The obtained F-value of 9.17; $dF=1,9$ for the sweetener effect allows us to conclude that the new sweetener produces a product that is notably less sweet than the sucrose-sweetened product and should not be substituted in the formulation.
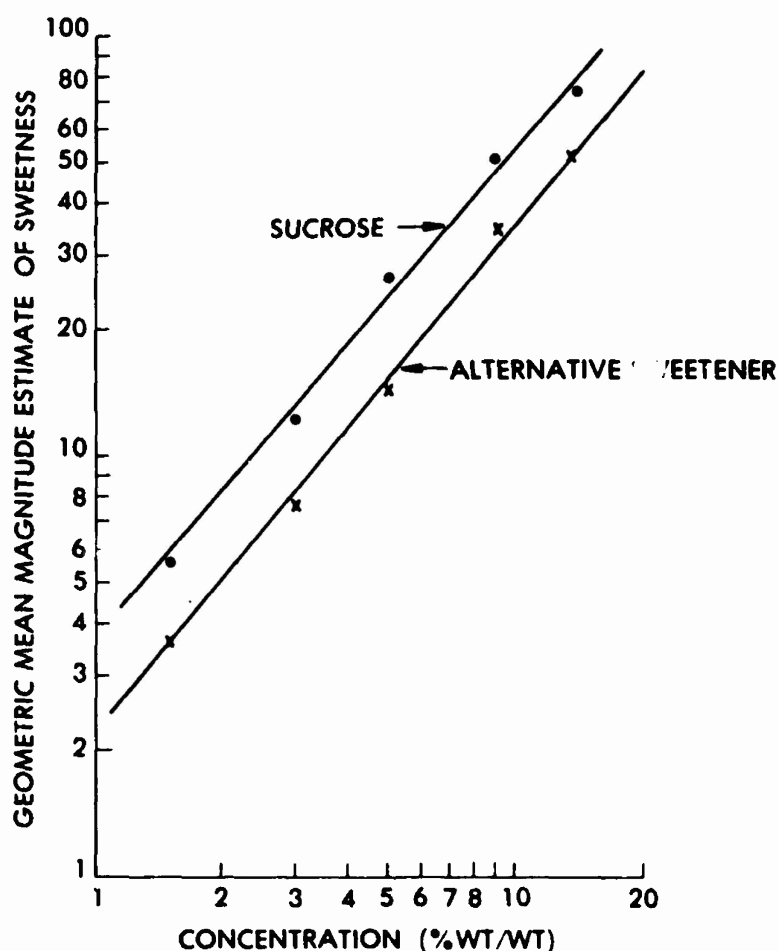
Figure 12. Plot of the geometric mean magnitude estimates of sweetness for the data in Table 5. The data are plotted in full logarithmic coordinates and the slopes of the best-fitting lines are approximately 1.2.

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VI. RELATING SENSORY AND INSTRUMENTAL DATA

By its definition, psychophysics requires analysis of the relationships existing between sensory and physical-chemical measures of stimuli. In the preceding sections we have reviewed the sensory techniques for both the qualitative and quantitative description of foods. With knowledge of these tools we can now interface these subjective methods and data with objective methods and data. The present section will briefly touch on the basic concepts of correlation and regression, and then move on to the more complicated multivariate data analysis techniques that are used frequently in contemporary food quality assessment.

A. Correlation and Regression

When one is dealing with only two variables, e.g., a sensory measure and an objective measure, the relationship between the two can be determined using the statistical techniques of correlation and regression. Keep in mind that correlation refers to the estimation of the **strength of relationship** between two variables, i.e., the degree to which one variable co-varies or co-relates with another and that regression refers to the **mathematical description of that relationship and the prediction of values of one variable based upon known values of the other variable.**

The relationships addressed by both correlation and regression techniques can be either linear or nonlinear in nature. When addressing presumed linear relationships, the standard Pearson product-moment coefficient (r) is the index of correlation that is most commonly used for continuous data sets. The mathematical derivations of this statistic (as well as others to be discussed) are not the goal of this chapter; however, the formulae for the application can be found in any standard text of statistics.[301-303] Alternative forms of this index for use with noncontinuous (dichotomous, ordinal) data are known as "phi", "point-biserial" and "rho" (Spearman rank-order coefficient), and a discussion of these coefficients can be found in more advanced statistical texts.[304]

[301]W.L. Hays. Statistics. New York: Holt, Rinehart and Winston, 1963.

[302]A.L. Edwards. Experimental Design in Psychological Research, rev. ed. New York: Rinehart and Company, 1960.

[303]B.J. Winer. Statistical Principles in Experimental Design, 2nd ed. New York: McGraw-Hill, 1971.

[304]J.C. Nunnally. Psychometric Theory. New York: McGraw-Hill, 1967.

Similar to linear correlation problems are linear regression problems. The difference is primarily in the fact that correlation analysis treats both variables as equivalent, while regression analysis treats one variable as an independent variable and the other variable as a dependent variable. Also, in regression analysis, a predictor (regression) equation is developed that allows prediction of raw scores on the dependent variable from raw scores on the independent variable. An excellent discussion of regression techniques can be found in the text by Mosteller and Tukey,[305] and numerous reviews and reports are available on the application of linear correlation and regression to assess the relationships between sensory and instrumental measures of food.[306-321]

[305]F. Mosteller and J.W. Tukey. Data Analysis and Regression: A Second Course in Statistics. Reading, MA: Addison-Wesley. 1977.

[306]L.B. Sjostrom. Correlation of objective-subjective methods as applied in the food field. In Correlation of Subjective-Objective Methods in the Study of Odors and Taste, Special Technical Publication No. 440. Philadelphia, PA: American Society for Testing and Materials, 1968.

[307]Correlations of Objective-Subjective Methods in the Study of Odors and Taste. Philadelphia, PA: American Society for Testing and Materials, 1969.

[308]J.J. Powers and H.R. Moskowitz (eds). Correlating Sensory-Objective Measurements, New Methods for Answering Old Problems. Philadelphia, PA: American Society for Testing and Materials, 1976.

[309]Objective Methods for Food Evaluation: Proceedings of a Symposium. Washington, DC: National Academy of Sciences, 1976.

[310]P.W. Voisey and E. Larmond. The effect of deformation rate on the relationship between sensory and instrumental measurements of meat tenderness by the Warner-Bratzler method. J. Inst. Can. Technol. Aliment., 10, 307 (1977).

[311]J. Loh and W.M. Breene. Texture analysis of textured soy protein products: Relations between instrumental and sensory evaluation. J. Texture Stud., 7, 405 (1977).

[312]D.J. Schmitt and J.T. Hoff. Use of graphic linear scales to measure rates of staling in beer. J. Food Sci., 44, 901 (1979).

[313]H.M. Soo and E.H. Sander. Prediction of sensory response to textural parameters of breaded shrimp shapes using Instron texture profile analysis. J. Food Sci., 42, 163 (1977).

(Continued)

(Continued)

[314]W.R. Forbus, Jr., S.D. Senter, B.G. Lyon, and H.P. Dupuy. Correlation of objective and subjective measurements of pecan kernel quality. J. Food Sci., 45, 1376 (1980).

[315]O. Panasiuk, F.B. Talley, and G.M. Sapers. Correlation between aroma and volatile composition of McIntosh apples. J. Food Sci., 45, 989 (1980).

[316]A.S. Trant, R.M. Pangborn, and A.C. Little. Potential fallacy of correlating hedonic responses with physical and chemical measurements. J. Food Sci., 46, 583 (1981).

[317]D.B. Min. Correlation of sensory evaluation and instrumental gas chromatographic analysis of edible oils. J. Food Sci., 46, 1453 (1981).

[318]R.R. Lin and V.N.M. Rao. Sensory physical and chemical properties of canned peaches. J. Food Sci., 47, 317 (1981).

[319]R.A. Segars, R.G. Hamel, and J.G. Kapsalis. Use of Poisson's ratio for objective-subjective texture correlations in beef. An apparatus for obtaining the required data. J. of Texture Stud., 8, 433 (1977).

[320]K.C. Diehl and D.D. Hamann. Relationships between sensory profile parameters and fundamental mechanical parameters for raw potatoes, melons and apples. J. of Texture Stud., 10, 401 (1979).

[321]J.G. Kapsalis, A. Kramer, and A.S. Szczesniak. Quantification of objective and sensory texture relations. In Texture Measurements of Foods. A. Kramer and A.S. Szczesniak (eds). Dordrecht, Holland: D. Reidel Publishing Company, 1973, 130.

Unfortunately, in sensory science, most sensory dimensions are not linearly related to underlying physical dimensions, as reflected in both Fechner's logarithmic law and Stevens' power law. Also, as mentioned previously, when relating hedonic measures to instrumental measures, non-linear (quadratic) equations become necessary.[322,323] Thus, techniques for assessing nonlinear relationships are essential. In general, when a specific nonlinear relationship is expected between two variables, it is possible that a transform of the original variables can be made, so that linear correlation and/or regression analysis can still be used. Fortunately, such "intrinsically linear" relationships include the two most frequently assessed

[322]H.R. Moskowitz. Relative importance of perceptual factors to consumer acceptance: Linear vs. quadratic analysis. J. Food Sci., 46, 244 (1981).

[323]H.R. Moskowitz. Relating subjective and instrumental measures: A psychophysical overview. J. Food Qual., 4, 15 (1981).

relationships in sensory science – logarithmic and power functions. As shown earlier in this chapter, two variables bearing a logarithmic relationship of the form $Y = a \log X$ can be linearized by plotting Y as a function of the log of X. Similarly, two variables bearing a power function relationship of the form $Y = ax^b$ can be linearized by plotting the log of Y against the log of X (see Figure 9). By making these transforms of the raw data, one can then apply linear regression techniques to find the best-fitting logarithmic or power function. Transforms of other intrinsically linear functions can be found in texts by Lewis[324] and Draper and Smith,[325] and procedures for determining these transforms can be found in the statistical literature.[326,327]

In those cases in which the relationship between two variables is intrinsically nonlinear or in which no specific nonlinear relationship is expected, then the best-fitting function must be found through the techniques of nonlinear regression. These latter techniques are beyond the scope of our discussion, but the interested reader should see the discussion presented in Draper and Smith.[325]

Two final reminders need to be made about simple linear and nonlinear correlation and regression before moving on to other topics. First, it must be understood that when a statistically significant relationship is found between two variables, this significance may be due to one of three causal relationships.

        X causes Y
        Y causes X
or   Z causes both X and Y

The third possibility, that some third variable may be responsible for the relationship between X and Y, means that one can never prudently infer causality between an instrumental measure and a sensory measure on the basis of a strong obtained correlation between them.

The second point is that correlation coefficients are merely estimates of the true relationship existing between the population variables, because the coefficients are based on only a sample of the entire population. Thus, significant correlation coefficients can occur by chance with some non-zero probability. The more correlation coefficients that are calculated, the greater the likelihood that some high correlations may be obtained by chance. The "shotgun" approach that is sometimes used in subjective/objective research,

[324]D. Lewis. Quantitative Methods in Psychology. New York: McGraw-Hill, 1960.

[325]N. Draper and H. Smith. Applied Regression Analysis. New York: Wiley, 1966.

[326]G.E.P. Box and D.R. Cox. An analysis of transformations. J. Roy. Statist. Soc., B-26, 211 (1964).

[327]G.E.P. Box and P.W. Tidwell. Transformation of the independent variables. Technometrics, 4, 531 (1962).

wherein several sensory measures and several objective measures are obtained on the same products, and correlations between all possible pairs of subjective and objective variables are calculated, maximizes the likelihood of obtaining chance correlations. A shotgun approach often results in misinterpretation of data, misleading conclusions and, frequently, meaningless results. The sensory/objective scientist must always be cognizant of this possibility and examine only theoretically relevant relationships or else apply the techniques of multiple correlation and regression to evaluate the relationship.

B.   Multivariate Methods

Due to the physical and sensory complexity of many foods, qualitative description of some products may involve as many as 40 or more descriptive attributes, and the number of instrumental measures that can be obtained from the food may also become large. Many of these attributes and measures may be redundant or be prima facie representatives of more fundamental underlying physical and perceptual dimensions. In order to evaluate these possibilities, a variety of multivariate techniques have been developed. Those of greatest importance for food quality assessment problems include cluster and/or factor analysis. multidimensional scaling, response surface methodology and multiple regression. We will first discuss the techniques that can be applied independently to sensory or instrumental data, i.e., cluster or factor analysis and multidimensional scaling, and then move on to the problem of relating the two sets of variables through multiple regression analysis.

1. Cluster, Factor and Principal Components Analyses

Cluster, factor and principle components analyses are techniques that are aimed at identifying the interrelationships or similarities among a set of variables (stimuli, sensory attributes, etc.). These procedures all attempt to reduce the original number of variables to a smaller number (called clusters, factors or components).

a. Cluster: Cluster analysis is a statistical technique in which the objective is to group elements of a stimulus or attribute variable into clusters, such that elements within a cluster are highly associated with one another, while elements of different clusters are relatively distinct from one another. For explanatory purposes, two examples of the use of cluster analysis will be presented. In the first example, cluster analysis is applied to ascertain the similarities and dissimilarities among a set of stimuli, whereas in the second example, it is applied to ascertain the relationships among a set of sensory descriptors.

Example: The first example is taken from data on the sensory evaluation of fresh fish fillets.[328,329] Eighteen different species of North Atlantic fish were evaluated on the basis of the texture, flavor and color of their cooked fillets by both texture and flavor profile panels. Each species was evaluated on a total of 18 attributes. The goal of the research was to group species together on the basis of similarities and/or dissimilarities in their sensory characteristics. Cluster analysis was applied to the data to establish these groupings or clusters.

By calculating correlation coefficients among all possible pairs of fish samples (using ratings on each of the sensory attributes as data pairs), a total of 153 (n (n-1)/2) coefficients were generated. The pair of fish species having the highest correlation coefficient was then grouped together to form the first cluster. Figure 13, which shows the results of the cluster analysis applied to these data, depicts this pair of maximally similar species at step 1. The species are tilefish and pollock, and they are joined together in the lowermost tree branch. At step 2, haddock is brought into the first cluster, indicating that, of all the remaining species of fish, haddock was the next most similar (had the next highest correlation). At step 3, white hake and whiting are joined together to reflect the fact that they are more similar (highly correlated) to one another than was any other species to the fish in the first cluster. The process continues until the entire tree diagram of species is completed at step 17.

Based on the results of the cluster analysis depicted in Figure 13, it was concluded that three broad clusters of fish exist in the data. One cluster consists of dark-fleshed, oily, flavorful fish (weakfish, striped bass, bluefish and mackerel) another consists of white-fleshed, low-fat, mild-tasting fish (these are represented by the right branch at step 16, which contains the sub-cluster of white hake and whiting) and a last cluster contains only swordfish.

In addition to exploratory searches for clusters, specific questions concerning clusters can be addressed by this method. For example, rather than taking the two species with the highest correlation as the core for the first cluster, one might have chosen a species of interest as the starting point of the analysis and then searched for the species that correlated most highly with it, and so forth. In this way one would be able to identify species that form a common cluster with any particular species of interest.

[328]A.V. Cardello, F.M. Sawyer, P. Prell, O. Maller, and J. Kapsalis. Sensory methodology for the classification of fish according to "edibility characteristics". Lebensm. Wiss. Technol., 16, 190 (1983).

[329]A.V. Cardello, F.M. Sawyer, O. Maller, and L. Digman. Sensory evaluation of the texture and appearance of 17 species of North Atlantic Fish. J. Food Sci., 47, 1818 (1982).
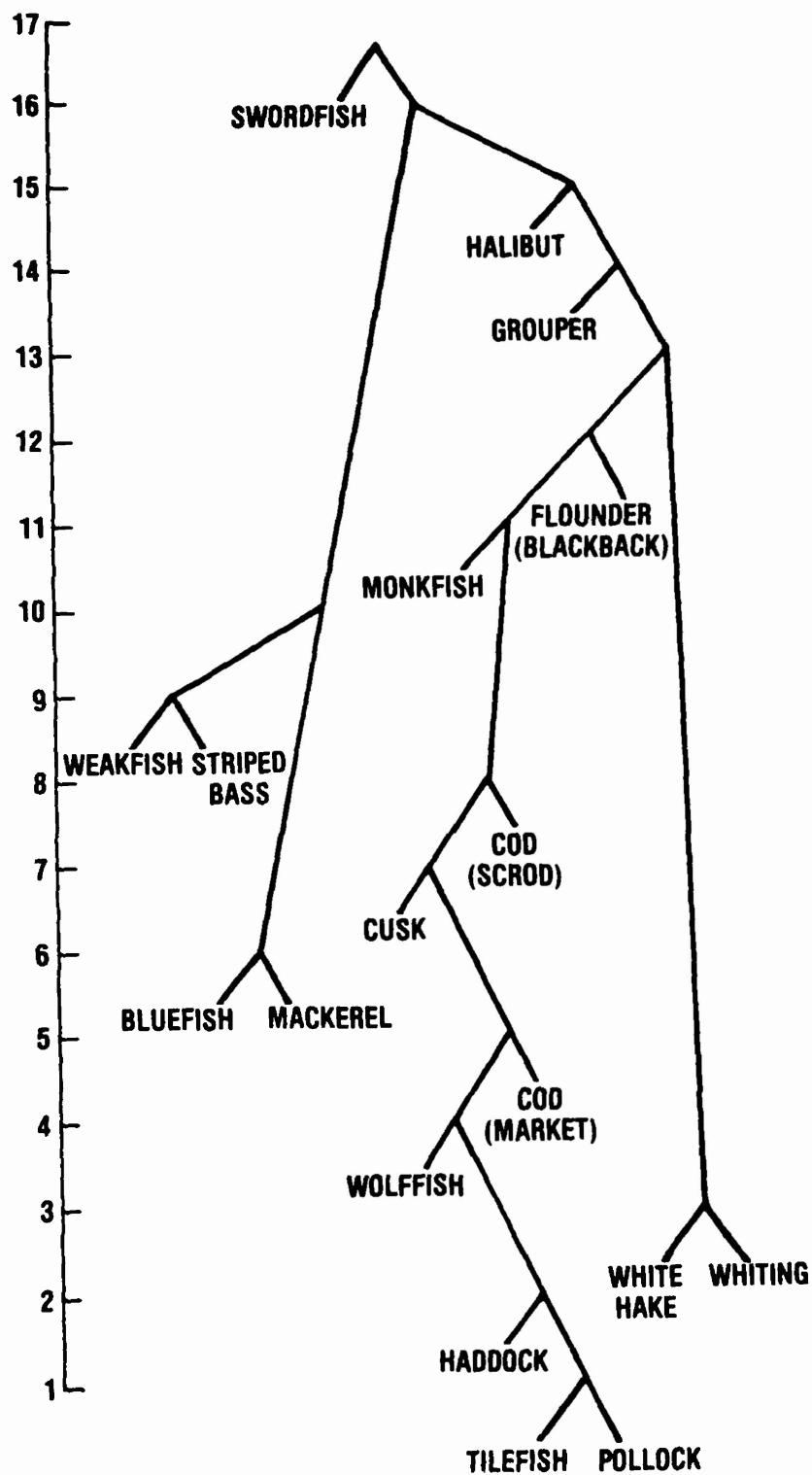
Figure 13. A tree-diagram representation of the results of cluster analysis applied to data on the sensory properties of fish.

The second example of an application of cluster analysis is taken from the literature[330,331] and uses green beans as the test food. Samples of fresh, canned and frozen green beans were evaluated by tasters' hedonic ratings of overall acceptability, color, flavor, appearance and mouthfeel. In addition, ratings on 20 sensory descriptors and 28 objective measures were obtained. The list of sensory and objective attributes appears in Table 6. Cluster analysis was applied to the data to assess the relationship of specific attributes to judgments of the acceptability of the flavor, mouthfeel, appearance and color of the products. In this case the problem of interest was to identify specific sensory descriptors and objective measures that are most correlated with the judged acceptability of the flavor (mouthfeel, appearance/color) of green beans. Given this objective, cluster analysis was conducted by successively designating the acceptability of the flavor, mouthfeel and appearance/color as the starting points for the analysis.

Table 7, derived from the study of Powers, Godwin and Bargmann,[330] is an analysis of terms comprising the various clusters, and provides insight into the variables contributing to the acceptability of the products. For example, it can be seen that brightness of color was positively correlated with the acceptability of the appearance/color of the product for subjects who preferred frozen beans. For those who preferred canned beans, however, brightness of color was negatively correlated with acceptability. Even more interesting is the fact that some attributes, such as "sweet", appear in all three clusters, possibly suggesting cross-modal associations of sweetness with certain appearance/color or mouthfeel attributes.

As is evident, cluster analysis is a useful tool for analyzing relationships in multivariate data. The interested reader can review other applications of this technique in the text by Anderberg.[332]

b. **Factor and Principal Components:** Factor analysis refers to a group of statistical techniques that can be used to search for underlying constructs among a group of measures (stepwise analysis) or to test hypotheses about the existence of such constructs (direct analysis). In stepwise analysis, two steps are involved. First, the set of test variables is **condensed** into a smaller set of factors, using one of a number of "condensation" techniques, and second, the resulting factors are **rotated** to determine the simplest or

[330]J.J. Powers, D.R. Godwin, and R.E. Bargmann. Relations between sensory and objective measurements for quality evaluations of green beans. In Flavor Quality-Objective Measurement. R.A. Scanlon (ed). Washington, DC: Am. Chem. Soc., 1977, 51.

[331]D.R. Godwin, R.E. Bargmann, and J.J. Powers. Use of cluster analysis to evaluate sensory-objective relations of processed green beans. J. Food Sci., 43, 1229 (1978).

[332]M.R. Anderberg. Cluster Analysis for Applications. New York: Academic Press, 1973.

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Table 6. Sensory attributes and objective measures obtained on canned and frozen green beans (from Godwin, Bargmann and Powers)[330]

Sensory Attributes	Objective Measures
Sweet	GLC peaks (17) designated
Buttery taste	#9, 10, 11, 12, 13, 20,
Green vegetable taste	24, 26, 32, 33, 24, 36
Hay-like flavor	37, 39, 40, 41 and 47
Bland	Absorbancy ratios @
Crisp	467/525 nm
Processed flavor	525/610 nm
Off-flavor	525/665 nm
Persistent aftertaste	LC peaks (4) designated
Pleasant aftertaste	#1, 2, 3 and 9
Coarse	Tensile strength
Juicy	Shear force
Slimy	Coefficient of friction:
Soggy	parallel to axis
Fibrous	perpendicular to axis
Tender	
Pale color	
Bright color	
Uniform appearance	

Table 7. Sensory attributes and objective variables comprising three clusters in the study by Godwin, Bargmann and Powers[330]

Appearance/Color Cluster	Flavor Cluster	Mouthfeel Cluster

1. Panelists preferring frozen beans

Appearance/Color Cluster	Flavor Cluster	Mouthfeel Cluster
+ Appearance	− Off-flavor	+ Coarse
+ Color	+ Pleasant aftertaste	+ Fibrous
− Color off-shade	+ Sweet	+ Bright color
+ Bright color	+ Flavor	− Pale color
− Pale color	− Processed flavor	− Shear force
− Processed flavor	− Soggy	− Absorbancy ratio @ 525/610 nm
− Absorbancy ratio @ 525/610 nm	− Color off-shade	− Color off-shade
− Soggy	− Pale color	− Processed flavor
− Slimy	− Slimy	+ Crisp
+ Green vegetable taste	+ Bright color	− Tender
	+ Green vegetable taste	+ Green vegetable taste
	− Absorbancy ratio @ 525/610 nm	− Soggy
		− Slimy

2. Panelists preferring canned beans

Appearance/Color Cluster	Flavor Cluster	Mouthfeel Cluster
+ Sweet	− Flavor	− Coarse
+ Pleasant aftertaste	− Hay-like flavor	+ Juicy
− Bright color	− Green vegetable taste	− Tender
+ Absorbancy ratio @ 525/610 nm	+ Sweet	− Fibrous
+ Appearance	− Off-flavor	+ Buttery taste
− LC Peak #9	+ Pleasant aftertaste	− Crisp
− Shear force	− Bright color	− Green vegetable taste
− GLC Peak #20	+ Absorbancy ratio @ 525/610 nm	+ Sweet
+ Persistent aftertaste		− Hay-like flavor
+ Color		+ Mouthfeel
		+ Off-flavor
		+ Pleasant aftertaste
		+ Absorbancy ratio @ 525/610 nm
		− Bright color

most easily interpretable set of factors. In the direct approach, the hypothesized constructs are directly tested, without searching for other constructs that may be present.

The stepwise factor analytic approach to identifying underlying perceptual dimensions from attribute ratings is to treat the factors as linear combinations of the individual attribute ratings, e.g., Factor $A = w_a a + w_b b + w_c c \ldots w_n n$, where a, b, c.....n are the attribute ratings and w_a, w_b, $w_c \ldots w_n$ are the weightings used for obtaining linear combinations. A number of different methods for deriving factors are based on the techniques that are used to obtain weightings. In the centroid method, for example, all weights are either +1.0 or -1.0, that is, attribute ratings are simply summed or subtracted from each other. However, several more complex methods of condensation are available, including the method of principal components, which selects weights for the first linear combination in such a way that the first factor explains the greatest amount of variability in the data.

Once the first factor has been determined, the computed factor score for each product can be correlated with each attribute. In order to find a second factor that is not correlated with the first, the loadings on the first factor are partialed out from the original correlation matrix to produce a new matrix of correlations. This new matrix shows the correlations among attributes when the effects of the first factor are removed. From this new matrix, a second factor is derived, and so forth, until all factors have been established. The resulting factor structure is geometrically represented by a set of orthogonal axes in a multivariate space.

In many applications, the condensation of the measured variables into a smaller set of factors that accounts for the greatest amount of variance is the desired endpoint. For this purpose the principal components method of condensation is the most useful approach, since it does exactly this. If the data analysis stops here, a principal components analysis is said to have been conducted on the data. Thus, the method of principal components analysis involves linear combinations of the original variables, without regard for underlying mathematical models of factor structure. In other words, principal components analysis deals with actual variables, while factor analysis deals with hypothetical variables. Depending on one's perspective, principal components analysis can be viewed as a form of factor analysis, or else the term "factor analysis" can be reserved for those multivariate approaches that attempt to derive hypothetical factors. Excellent discussions of both approaches, their similarities and their differences can be found in the texts by Harman,[333] Mulaik[334] and Harris.[335]

[333]H.H. Harman. Modern Factor Analysis, 2nd ed. Chicago, IL: Univ. Chicago Press, 1967.

[334]S.A. Mulaik. The Foundations of Factor Analysis. San Francisco, CA: McGraw-Hill, 1972.

[335]R.J. Harris. A Primer of Multivariate Statistics. New York: Academic Press, 1975.

As mentioned earlier, in addition to condensing a large set of sensory attributes into a smaller set of fundamental sensory dimensions, many multivariate techniques also provide geometrical representations of the data. What makes these representations possible is that correlation coefficients vary from -1.0 to +1.0, as do the cosines of angles. Thus, any correlation coefficient (r) between two variables can be expressed as two vectors subtending an angle of acos (r). Figure 14 depicts the correlation of four variables (a, b, c and d) with a fifth variable (e). The correlations of a with e (r_{ae}), b with e (r_{be}), c with e (r_{ce}) and d with e (r_{de}) are 0.0, +0.70, +1.0 and -0.50, respectively. Since r_{ae} = 0.0 and acos (0) = 90°), the correlation of a with e can be depicted by two perpendicular vectors (vectors A and E). Similarly, since r_{be} = 0.70, and acos (r_{be}) = 45° the correlation can be depicted by vectors B and E. Since r_{ce} = 1.0 and acos (r_{ce}) = 0°, the correlation is depicted by the superimposed vectors C and E. The correlation of d with e is negative, r_{de} = -0.50, acos (r_{de}) = 120° and the correlation is depicted by vectors subtending an angle greater than 90° (vectors D and E). Inversely, if we look at vectors A and B, we know that the angle between them is 45°; therefore, the correlation coefficient between them must be 0.50. In this way, the correlations among all pairs of variables can be determined and the vectors of Figure 14 can be shown to be a geometrical of the correlation matrix shown in Table 8.
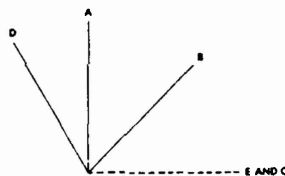
Figure 14. Vector representation of the correlation matrix in Table 8.

Table 8. A correlation matrix showing the correlation coefficients among five variables (a, b, c, d and e).

	a	b	c	d	e
a	1.00	0.70	0.00	0.87	0.00
b	0.70	1.00	0.70	0.26	0.70
c	0.00	0.70	1.00	-0.50	1.00
d	0.87	0.26	-0.50	1.00	-0.50
e	0.00	0.70	1.00	-0.50	1.00

Although any correlation matrix can be depicted by vector geometry, the representation in Figure 14 is unusual because all of the correlations can be represented in just two dimensions. In factor analytic applications, such a situation indicates that there are two factors underlying the five variables. More frequently, a large number of variables would result in a multidimensional space, with each dimension of the space representing a separate factor. If the dimensions required to define the space are all orthogonal, then the factors are not correlated with one another. In this way a new "factor space" can be used to represent the original data, with the individual factors also represented as vectors in the space. The angles between the factor vectors and the vectors for individual variables represent the "factor loadings" for each, i.e., the amount of variability in the measure accounted for by the factor. However, to facilitate interpretation of factors, factor vectors are usually rotated so as to maximize loadings on one or more variables. Such rotation does not affect the total amount of variability accounted for by the factors but merely maximizes the correlation between one or more factors and one or more variables, so that those factors can be most easily interpreted in terms of the original variables.

Example: A recent example of the use of stepwise maximum likelihood factor analysis involved the analysis of sensory terms for wine description.[336] The study of wine descriptors is ideally suited to factor analytic techniques because of the wealth of terms used in wine description, many of which may be highly correlated with one another. A total of 33 descriptors for wine were selected and used by 37 judges to rate each of 14 red wines. A rating of acceptability was also obtained. The list of 33 descriptors, as well as the eight factors which were identified appear in Table 9. The descriptor following each factor number is the interpretation given to the factor by the investigators. Note should be taken that conceptually similar attributes have the same direction (positive or negative) of loading on the factor, while dissimilar attributes have opposite loadings. Thus, on Factor 1 (pungency) the terms "tart", "biting", "astringent", "sharp", "bitter", "dry" and "vinegar" all have positive loadings, while "sweet" and "coarse" have negative loadings. As in the cluster analytic study of sensory descriptors for green beans, cited earlier, it is possible to assess those sensory descriptors most associated with acceptability of the product. Factor 2 (overall quality) shows a high degree of association between the acceptability of red wines and the attributes of "hearty", "mature", "balanced", "desirable aftertaste" and "winey".

[336]L.S. Wu, R.E. Bargman, and J.J. Powers. Factor analysis applied to wine descriptors. J. Food Sci., 42, 944 (1977).

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Table 9. List of sensory descriptors used in a factor-analytic study of wine descriptors. The eight obtained factors and the loading of each attribute on the factors are also shown (data taken from Wu, Bargmann and Powers).336

Sensory Descriptors

tart
dry
sweet
bitter
salty
metallic
biting
astringent (puckery)
smooth
coarse
syrupy
watery
aromatic
hearty
delicate (soft, light)
insipid (flat)
medicinal
sharp
winey
fruity
grapey
woody
musty (earthy, moldy)
musk-like
yeasty
burnt-smokey
spicy
vinegary
sulfurous
fresh
mature
balanced (round)
desirable aftertaste

Factors

1. Pungency

Tart	0.55
Biting	0.52
Astringent	0.46
Sharp	0.46
Bitter	0.42
Dry	0.35
vinegary	0.35
Sweet	-0.33
Coarse	-0.26

2. Overall Quality

	0.39
Mature	0.61
Balanced	0.58
Hearty	0.50
Desirable Aftertaste	0.39
Winey	0.21
Acceptability	0.20

3. Smoothness vs. coarseness

Coarse	-0.43
Smooth	0.37
Medicinal	0.32
Metallic	0.27
Desirable Aftertaste	0.25
Delicate	0.20

4. Sweetness vs. dryness

Sweet	0.42
Syrupy	0.36
Dry	-0.35
Medicinal	0.29
Watery	-0.25
Tart	-0.22

5. Flavor

Watery	0.37
Insipid	0.26
Hearty	-0.24
Delicate	0.24
Syrupy	-0.22

6. Disagreeableness (1)

Insipid	0.29
Musty	0.28
Bitter	0.26

7. Fruitiness

Grapey	0.59
Fruity	0.58
Winey	0.36

8. Disagreeableness (2)

Medicinal	0.58
Insipid	0.46
Metallic	0.45

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Similar analyses of sensory descriptors have been carried out on green beans,[330] puddings, custards, gelatins and whipped toppings,[337] food preferences,[338] wine,[339,340] beef texture,[341] simple odorants,[342] snack foods,[343] chicken texture,[344] meats[345] and other foods.[346-349]

[337] W.F. Henry, M.H. Katz, F.J. Pilgrim, and A.T. May. Texture of semi-solid foods: Sensory and physical correlates. J. Food Sci., 36, 155 (1971),

[338] F.J. Pilgrim and J.M. Kamen. Patterns of food preferences through factor analysis. J. Marketing, 24, 68 (1959).

[339] G.A. Baker. Organoleptic ratings and analytical data for wines analyzed into orthogonal factors. Food Res., 19, 575 (1954).

[340] W.O. Kwan and B.R. Kowalski. Data analysis of sensory scores: Evaluations of panelists and wine score cards. J. Food Sci., 45, 213 (1980).

[341] J.M. Harries, D.N. Rhodes and B.B. Chrystall. Meat texture: I. Subjective assessment of the texture of cooked beef. J. Texture Stud., 3, 101 (1972).

[342] E.H. Hsu. A factorial analysis of olfaction. Psychometrika, 11, 31 (1946).

[343] J.S. Jellinek. The meanings of flavors and textures. Food Technol., 27 (1973).

[344] J.E.R. Frijters. Evaluation of a texture profile for cooked chicken breast meat by principal component analysis. Poultry Sci., 55, 229 (1976).

[345] S. Horsfield and L.J. Taylor. Exploring the relationship between sensory data and acceptability of meat. J. Sci. Food Agri., 27, 1044 (1976).

[346] J. Toda, F. Wada, K. Yasumatsu, and K. Ishili. Application of principal component analysis to food texture measurements. J. Texture Stud., 2, 207 (1971).

[347] S. Yoshikawa, S. Nishimaru, T. Tashiro and M. Yoshida. Collection and classification of words for description of food texture, III: Classification by multivariate analysis. J. Texture Stud., 1, 452 (1970).

[348] A.M. Vickers and C.M. Christensen. Relationships between sensory crispness and other sensory and instrumental parameters. J. of Texture Stud., 11, 291 (1980).

[349] H.R. Moskowitz and J.G. Kapsalis. Psychophysical relations in texture. In Rheology and Texture in Food Quality. J.M. deMan, P.M. Voisey, V.F. Rasper, and D.W. Stanley (eds). Westport, CN: AVI Publishing Co., Inc., 1976, 554.

2. Multidimensional Scaling

Multidimensional scaling is a multivariate statistical technique that allows the investigator to (1) uncover basic perceptual dimensions underlying the sensory appreciation of foods, and (2) represent the relationship among stimuli through a multidimensional geometric space. Thus, unlike cluster and factor analytic techniques, in which the sensory attributes are chosen before data collection can begin, the purpose of multidimensional scaling is to uncover these basic sensory attributes. The raw input to a multidimensional analysis consists of judgments of the similarities or dissimilarities among element pairs in the stimulus set. The nature of the panel judgments may be either metric (interval or ratio) or nonmetric (ordinal), with appropriate algorithms available for both types of measures.

Upon obtaining similarity (or dissimilarity) judgments of the pairs of stimuli, the resulting matrix of judgments is treated as a matrix of perceptual distances. Through the mathematics of "proximities analysis", the rubric under which these techniques are subsumed, a hyperspace is generated, in which all of the stimuli are represented as points in the space. Stimuli that are perceived as being similar to one another are located in close proximity to one another, while stimuli that are perceived as different from one another are located at a distance from one another. Each dimension within the hyperspace may be interpreted as a fundamental perceptual dimension, based on prior knowledge of the nature of the stimuli located along the dimensions. A good analogy to the general procedure of multidimensional scaling is to consider the matrix of similarities or dissimilarities as a mileage chart showing distances between cities in the United States. Just as one can work backwards from this mileage chart to reconstruct the map of the United States, one can work backwards from the similarities maxtrix to reconstruct the perceptual map of judged stimuli; although the perceptual map, unlike the map of the United States, may be in 1, 2, 3 or more dimensions. Furthermore, as in factor analysis, each dimension requires interpretation based on prior knowledge of the sensory properties of the stimulus. Usually, the first dimension of the multidimensional space is a hedonic (like-dislike) dimension, although other dimensions will vary with the set of stimuli being scaled.

The popularity of the multidimensional scaling approach for studying the qualitative similarity among stimuli has resulted in a proliferation of computer programs for analyzing multidimensional scaling data. These programs include M-D-SCAL,[350] INDSCAL,[351] SINDSCAL,[352] TORSCA[353] and ALSCAL.[354]

Examples: Figure 15 shows a three-dimensional solution for similarity judgments of the sensory characteristics of six fish species. The data were generated by ALSCAL, using a set of similarity judgments made by 19 sensory panelists.[355] Dimension 1 is a color dimension. Mackerel, a dark-fleshed fish, loads high on this dimension, while halibut, white hake and haddock, which are all white-fleshed, load high on the other end of this dimension. Dimension 2 is a flakiness dimension, since halibut and mackerel have little flakiness, while haddock and white hake are very flaky. Lastly, Dimension 3 is a flavor dimension, with mackerel, a highly flavorful, oily fish falling at one extreme and the mild-flavored haddock and flounder falling at the other extreme. Based on these data it can be concluded that color of flesh, flakiness and flavor intensity are the three primary perceptual dimensions of these fish species.

[350]J. Kruskal and F. Carmone. How to use MDSCAL-5-M and other useful information, Unpublished document. Murray Hill, NJ: Bell Telephone Laboratories, 1969.

[351]J.D. Carroll and J.J. Chang. How to use INDSCAL, a program for the analysis of individual differences multidimensional scaling, Unpublished document. Murray Hill, NJ: Bell Telephone Laboratories, 1971.

[352]S. Pruzansky. How to use SINDSCAL, A computer program for individual differences in multidimensional scaling. Murray Hill, NJ: Bell Telephone Laboratories, 1975.

[353]F.W. Young and W.S. Torgerson. TORSCA, a FORTRAN IV program for Shepard-Kruskal multidimensional scaling analysis. Behav. Sci., 12, 498 (1967).

[354]Y. Takone, F.W. Young, and J. de Leeuw. Nonmetric individual differences in multidimensional scaling: On alternating least squares method with optimal scaling features. Psychometrika, 42, 7 (1977).

[355]A.V. Cardello, O. Maller, J. Kapsalis, R.A. Segars, F.M. Sawyer, C. Murphy, and H.R. Moskowitz. The perception of texture by trained and consumer panelists. J. Food Sci., 47, 1186 (1982).

Figure 15.   Three-dimensional solution for similarity judgments
on six species of fish.

While the technique of multidimensional scaling is a powerful tool for
investigating the qualitative dimensions of food, one practical drawback of
the method is the large number of stimulus presentations that are required.
If x stimuli are to be evaluated, then in order to present all possible pairs
of stimuli, a total of $(x^2 - x)/2$ presentations are needed. An alternative
technique that reduces the requirement on the number of presentations is
"multidimensional unfolding."[350,356,357] This technique requires that each

[356]C. Coombs. A Theory of Data. New York: Wiley, 1964.

[357]J.D. Carroll and J.J. Chang. Relating preference data to multidimensional
scaling solutions via a generalization of Coomb's unfolding model. Murray
Hill, NJ: Bell Telephone Laboratory, 1971.

stimulus be profiled, using a series of sensory descriptors. The resulting matrix of ratings is then treated as a distance matrix, as previously discussed, and a geometrical map is generated, into which are embedded both stimuli and descriptor words. While this technique eliminates the requirement of large numbers of stimulus presentations and the interpretation of dimensions, it does require prior information about the relevant sensory dimension of the stimuli to be profiled.

Figure 16 shows geometrical spaces generated for a series of salts using the multidimensional unfolding approach.[30] These data were obtained by having panelists profile the taste of 15 different salts. Profiles were generated by having the panelists apportion magnitude estimates of intensity among the "salty", "sour", "sweet" and "bitter" taste qualities. Each space is for a different concentration of salt. As can be seen, both the stimuli (salts) and the descriptors (taste attributes) are embedded within the same space, unlike Figure 15, where only the stimuli are embedded in the space. These data are interpreted in terms of the location and distance of stimuli to descriptors. For example, at all concentrations two major dimensions emerge - a bitter/salty dimension and a bitter/salty - sour/sweet dimension. Also, at .1080M, LiCl and NaCl are more salty than any of the other salts (due to their greater proximity to the point labeled "salty") and both are more similar to one another than either is to any other salt (due to their closer proximity to one another).

For those interested in the application of multidimensional scaling to represent qualitative similarity among food-related stimuli, several important studies have been conducted on odorants,[358-367] tastants[368-376] and more complex stimuli.[377-383]

[358]M.H. Woskow. Multidimensional scaling of odors. In Theories of Odor and Odor Measurement. N. Tanyolac (ed). New York: Circa Publications, 1968, 147.

[359]M. Yoshida. Psychometric classification of odors (6). Jap. Psychol. Res., 14, 70 (1972).

[360]B. Berglund, U. Berglund, T. Engen, and G. Ekman. Multidimensional scaling of twenty-one odors. Report 345. Sweden: Psychological Laboratories, University of Stockholm, 1972.

[361]H.R. Moskowitz and C. Gerbers. Dimensional salience of odors. Ann. N.Y. Acad. Sci., 237 (1974).

[362]S.S. Schiffman. Physicochemical correlates of olfactory quality. Science, 112, 185 (1974).

[363]D.M. Alabran, H.R. Moskowitz, and A.F. Mabrouk. Carrot-root oil components and their dimensional characterization of aroma. J. Agric. & Food Chem., 23, 229 (1975).

Figure 16. Results of multidimensional unfolding applied to data on the taste of halide salts. Each of the four three-dimensional solutions is for a single concentration of the different scales.

(Continued)

[364]H.R. Moskowitz and C.D. Barbe. Psychometric analysis of food aromas by profiling and multidimensional scaling. J. Food Sci., 41, 567 (1976).

[365]H.R. Moskowitz. Multidimensional scaling of odorants and mixtures. Lebensm. Wiss. Technol., 9, 232 (1976).

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3. Discriminant Analysis

Discriminant analysis is a multivariate technique aimed at determining which of a set of variables best discriminates one group of objects from another. In typical food industry applications the predictor variables are either instrumental measures of foods, ratings of sensory attributes of foods or a combination of objective and sensory measures. The predictor groups are nominal classifications of the food items, such as "high quality" vs. "low quality" or "sweet" vs. "sour" vs. "bitter". Through discriminant analysis, a combination of weighted predictor variables (a discriminant function) is determined that classifies the test samples into their nominal categories.

Mathematically, linear discriminant analysis and factor analysis are closely related. The discriminant function, being a combination of weighted variables, can be viewed as a factor. Furthermore, linear discriminant functions can be obtained by applying principal component factoring to a matrix of data. However, rather than these data consisting of correlation coefficients among variables, they comprise measures of discrimination within and among the predetermined groups or categories. The factor loadings obtained from this analysis define the weights of the discriminant function. In simple linear discriminant analysis, a series of predictor variables are used to discriminate among only two nominal groups. In multiple linear discriminant analysis, the predictor variables are used to discriminate among three or more nominal groups. In the latter condition, a series of discriminant functions can be obtained, with the number of possible functions equaling one less than the number of nominal groups. Because each function is obtained by successive principal component factoring, each discriminant function is uncorrelated (orthogonal) with other obtained functions.

(Continued)

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[383]S.S. Schiffman. Multidimensional scaling: A useful tool to measure flavor. Cereal Foods World, 21, 64 (1976).

A simple graphic representation of the problem of discriminant analysis can be seen in Figure 17. In this example biscuits are first classified as being either "fresh" (f) or "stale" (s). A number of sensory attributes of the biscuits are then rated by a sensory panel. The two attributes depicted in Figure 17 are "hardness" (V_1) and "fracturability" (V_2). By plotting the ratings of each biscuit (f or s) on each variable, the data in Figure 17 reveal groupings of the two different classes of biscuits at two different loci in space. The mean ratings for each group of biscuits on the two variables are plotted as f and s and the dispersion about the means and overlap of data points are depicted by the two overlapping circles. By determining various linear combinations (D_1.....n) of V_1 and V_2, plots of the combination scores for the two groups of biscuits can be made, as shown in Figure 18. The linear combination (D) of variables V_1 and V_2 that produces the greatest spread in the distributions of Figure 18 is taken as the discriminant function. The criterion for choice of D is that it be the weighted linear combination that maximizes the F ratio.
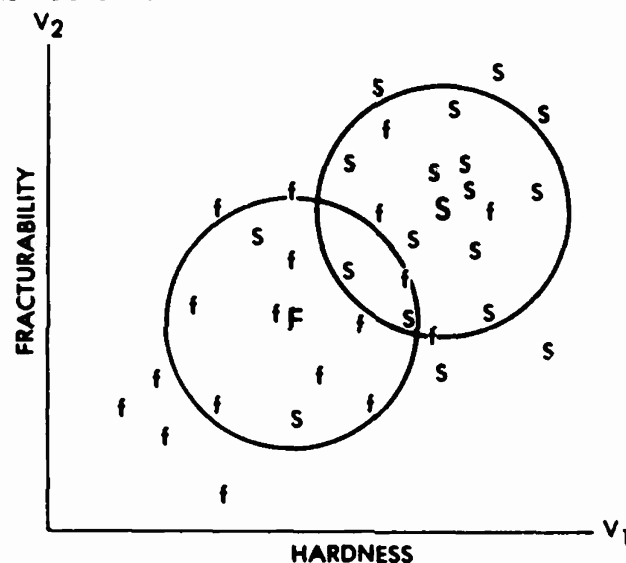
Figure 17. Plot of sensory judgments of fracturability as a function of hardness for biscuits designated as either fresh (f) or stale (s). The centroid (mean value) for both sets of biscuits is labeled F and S.
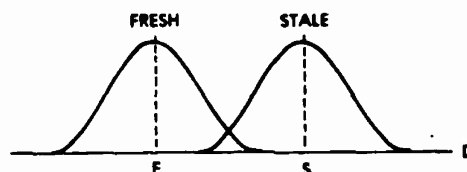

Figure 18. Hypothetical frequency distribution of scores on some linear combination of the variables in Figure 17. Discriminant analysis seeks that linear combination that maximizes the distance between F, S, and D.

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$$\frac{\text{Variance between means on D}}{\text{Variance within groups on D}} \tag{9}$$

While the techniques of discriminant analysis will enable selection of a set of weights for n predictor variables to produce maximum discrimination among the identified groups of objects, in many circumstances the time and cost involved in repeatedly obtaining information on all n variables is prohibitive. What is often needed is the best function that includes as few of the n variables as possible. The methods by which the "best function" can be selected each define a separate type of discriminant analysis. The four most common methods are (1) forward addition, (2) backward elimination, (3) stepwise, and (4) all possible functions.

In the **forward addition** procedure, each of the n individual variables are assessed for their effectiveness in discriminating among the samples, based on their F-ratio. The variable with the greatest F-ratio is selected first. This variable is then paired with each of the remaining n-1 variables. The variable, which, when paired with the first, produces the greatest discrimination among samples is selected as the second variable. This process continues, adding variables to the function that provide the greatest increment in discrimination power over that provided by the previously selected variables, and testing that this increment is of some criterion value. If at any point the new variable does not add significantly more discriminating power to the function, the process (computer program) terminates.

The **backward elimination** procedure works in the opposite manner to forward addition. In this procedure, all variables are initially included. Then the variable which, when eliminated from the function, reduces the discrimination power the least, is removed. At each step a new variable is eliminated until the elimination of a variable produces a criterion loss in discrimination power.

The **stepwise** procedure is the same as the forward addition procedure except that after each new variable is added to the function all previously selected variables are reexamined to determine whether, with the addition of the new variable, they now provide a level of discrimination power that is below criterion. If any variable is found to fall below criterion, it is eliminated from the function. The process continues until no more variables can be added and no more can be eliminated.

The last procedure is known as **all possible** functions, and as its name implies, this procedure examines the discrimination power provided by all possible discriminant functions and selects the best 1, 2, 3 .....n variable functions. The discrimination power provided by the best 1-variable function is then compared to that of the best 2-variable function and a decision is made on whether the addition of the new variable is justified by the increment in discrimination power. The process continues until the addition of another variable is not justified.

Example: An example of the use of stepwise discriminant analysis to classify gels on the basis of sensory and instrumental measures was provided by Levitt.[384] Sixty-one samples representing eight different gels, varying in texture, were evaluated by a seven-member texture profile panel on nine sensory attributes. In addition, each of the gels was evaluated on six instrumental variables. The list of texture attributes and instrumental measures appears in Table 10.

Table 10. List of sensory attributes and objective measures obtained on 61 samples of gels in the study by Levitt.[384]

Sensory Attributes	Objective Measures
Immobility	Peak height (yield stress)
Mobility	Distance to peak (compression at yield)
Recovery	Minimum height (minimum stress)
Breakdown A	Distance to minimum (compression at minimum)
Breakdown B	Slope between maximum and minimum
Cohesiveness	Minimum yield/stress ratio
Particle size	
Particle hardness	
Resistance	

[384]D.J. Levitt. The use of sensory and instrumental measurement of organoleptic characteristics via multivariate statistical methods. J. Texture Stud., 5, 183 (1974).

Stepwise discriminant analysis of the sensory data produced the results shown in Table 11. Only the first six steps are presented, as it was decided on practical grounds that only six sensory variables could be used in future work. At the first step, attribute K was entered into the function, indicating that attribute K was the best discriminator (largest F value) among the eight gels. The U-statistic in the last column is a measure of how close the function, at this step in the analysis, comes to classifying the gels perfectly. At step 2, attribute M was entered into the function, based on an F-value of 48.45, and the U-statistic reflects the improvement in classification provided by the addition of this variable. This process continued until attributes S, B, I and O were also added. Thus, the results of the discriminant analysis indicated that appropriate combination of attributes K, M, S, B, I and O will effect a high degree of accuracy in classifying the gels into eight distinct groups. Table 12 shows the actual classification of gels based on the discriminant function defined in step 6. As can be seen, a total of 58 of 61 gels is appropriately classified into these eight groups.

Table 11. Results of stepwise discriminant analysis for the sensory data of Levitt.[384] The variable included at each step, the F to enter and the calculated U-value are shown.

Step	Variable Included	F to Enter	U-Statistic
1	Breakdown A	170.33	0.0426
2	Breakdown B	48.45	0.0057
3	Particle Hardness	17.40	0.0017
4	Resistance	7.44	0.0008
5	Recovery	4.97	0.0005
6	Cohesiveness	3.08	0.0003

Table 12. Classification matrix obtained through use of the six sensory variables identified in Table 11. Entries indicate the number of samples of each gel type (left-most column) classified as being in each of the eight corresponding groups (from Levitt[384]).

Gel	Group								
	1	2	3	4	5	6	7	8	Total
1	8	0	0	0	0	0	0	0	8
2	0	8	0	0	0	0	0	0	8
3	0	0	6	0	0	0	0	0	6
4	0	1	0	7	0	0	0	0	8
5	0	0	0	0	8	0	0	0	8
6	0	0	0	0	0	8	0	0	8
7	0	1	1	0	0	0	5	0	7
8	0	0	0	0	0	0	0	8	8
	(Correct classifications = 58)								61

Table 13 shows the results for the stepwise analysis performed on the instrumental measures. In this case a criterion F of 1.5 was adopted to include the variable in the function. As reflected by the values of the U-statistics in steps 3 and 4, perfect discrimination (classification) of the gels was achieved.

Table 13. Results of stepwise discriminant analysis for the objective data of Levitt.[384] The variable included at each step, the F to enter and the evaluated U-value are shown.

Step	Variable Included	F to Enter	U-Statistic
1	Distance to peak	696.58	0.0108
2	Minimum height	137.98	0.0005
3	Peak height	135.19	0.0000
4	Minimum yield/stress ratio	39.76	0.0000

In addition to the study of gels by Levitt,[384] a variety of studies have applied the techniques of discriminant analysis to problems of food classification. Some of these recent studies have included the discrimination of flavor quality of coffee by gas chromatography (GC) measures,[385] the quality of beer by GC analysis of headspace volatiles and other physicochemical measures,[386,387] brands of cola beverage by sensory

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judgments,[338] the flavor quality of bourbon and blueberry-whey beverage by GC measures,[389] the flavor quality of grape jelly by instrumental texture and gas-liquid chromatography (GLC) measures,[390] tomato juice blends and roasts of peanuts by GLC measures,[391] the flavor character of corn by GC measures,[392] mixtures of odorous compounds by GLC analysis,[393] and the aroma of meat[394] and other protein sources[395] by GC headspace analysis.

[388]L.L. Young, R.E. Bargmann, and J.J. Powers. Correlation between gas-liquid chromatographic patterns and flavor evaluation of chemical mixtures and of cola beverages. J. Food Sci., 35, 219 (1970).

[389]J.J. Powers and M.C. Quinlan. Refining of methods for subjective-objective evaluation of flavor. J. Agr. Food Chem., 22, 744 (1974).

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[392]A. Dravnieks, H.G. Reilich, J. Whitfield, and C.A. Watson. Classification of corn odor by statistical analysis of gas chromatographic headspace volatiles. J. Food Sci., 34, 38 (1973).

[393]J.J. Powers and M.C. Quinlan. Subjective-objective evaluation of model odor systems. Lebensm. Wiss. Technol., 6, 209 (1973).

[394]I.H. Quist, E.C.F. von Sydow, and C.A. Akesson. Unconventional proteins as aroma precursors: Instrumental and sensory analysis of the volatile compounds in a canned meat product containing soy or rapeseed protein. Lebensm. Wiss. Technol., 9, 311 (1976).

[395]I.H. Quist and E.C.F. von Sydow. Unconventional proteins as aroma precursors: Sensory analysis of heat treated soy and rapeseed protein model systems. Lebensm. Wiss. Technol., 9, 299 (1976).

In spite of the above successes, one important problem of discriminant analysis must be pointed out. This is the fact that the techniques do not take into account the theoretical relevance of one variable over another or the cost of one variable over another. Thus, if one or more predictor variables that have been previously demonstrated to be directly related to the predictant variable are, by chance, highly correlated with other **irrelevant** predictor variables, they may be eliminated from the function in favor of the correlated variables. Similarly, if two variables are highly correlated and effect equal discrimination, but one is significantly less time-consuming or costly to obtain measurements on, then this variable should be chosen for inclusion, rather than its correlated variable. However, the mathematical techniques are impartial to these distinctions and the more desirable variable may be eliminated in favor of the less desirable variable. These problems of colinearity among variables can be minimized by using common sense in interpreting t.. data from discriminant analyses and "forcing in" variables when necessary for theoretical or practical reasons.

4. Multiple Regression

Multiple regression is a statistical technique that is similar to discriminant analysis, and is an essential technique for relating objective to subjective data on food quality. As in discriminant analysis, a series of n metric predictor variables (objective measures) are employed to predict some dependent variable (sensory measure). However, unlike discriminant analysis, in which the dependent variable is usually nominal in nature, the dependent variable in multiple regression is a metric variable. In the food industry the most common use of multiple regression techniques is to predict the magnitude of some sensory attribute based on a series of objective measures of the food. However, in theory, any combination of objective and/or sensory variables can be used to predict any other objective or sensory measure.

The parallel between multiple regression analysis and discriminant analysis extends to the classification of multiple regression approaches by the method used to define the "best regression function." As in discriminant analysis, these methods are **forward addition, backward elimination, stepwise,** and all possible functions. For multiple regression, we can think of these methods as ways of choosing variables from a correlation matrix of pairs of predictor and predictant variables. The forward addition procedure begins by choosing the predictor variable that has the best simple linear correlation with the predictant variable. This variable becomes the first variable of the multiple regression function and its effect is partialed out from all other variables. In the second step the predictor variable with the highest partial correlation with the predictant variable is chosen and included in the regression function. The multiple correlation coefficient (R^2) is then computed using the two predictor variables. If the R^2 so determined accounts for a significant amount of variation over that provided by the first variable alone, then the added variable is retained in the function and the process continues, terminating when addition of a new variable does not provide a significant variance increment in R^2. The procedures of backward elimination, stepwise, and all possible functions parallel those described for discriminant analysis but involve choices and decisions made on R^2 values.

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Example: In one study of the correlation between subjective (sensory) and objective (instrumental) measures of the texture of cooked meat, stepwise multiple regression analysis was used in an attempt to predict the sensory attributes of tenderness and juiciness from instrumental measures of Instron compression (IC), Warner-Bratzler shear (WB), adhesion (Ad), and cooking loss (CL).[396] Using cubes of meat as test samples, the obtained regression function for tenderness (T) was

$$T = 1.40 \ IC + 0.60 \ WB + 0.116 \ CL - 2.61$$
$$(R^2 = .834) \tag{10}$$

The corresponding equation for juiciness (J) was

$$J = 0.243 \ CL - 0.25 \ WB + 1.36$$
$$(R^2 = .815) \tag{11}$$

Thus, 83% of the variability in ratings of tenderness could be explained by a linear combination of Instron compression, Warner-Bratzler shear and cooking loss measures. Similarly 81% of the variability in ratings of juiciness could be explained using only two instrumental measures – cooking loss and Warner-Bratzler shear.

The approach of multiple regression analysis, as described above, has advantages over simple linear regression approaches in which each sensory measure is regressed against each instrumental measure, in the hope that one pair will correlate highly. As discussed previously, in such approaches the likelihood of finding high correlations by chance increases monotonically with the number of correlations attempted. Some of the many studies employing multiple regression have used it to predict consumer acceptance of fish from objective measures,[397] intensity of ginger flavor from GC peaks,[398] flavor of soy sauce from GC analysis,[399] acceptance of green beans from judgments of flavor, mouthful, appearance and color,[330] acceptance of bourbon and peaches fro. color, flavor, appearance and texture,[389] factor loadings for semisolid

[396]P.E. Boston, A.L. For, P.V. Harris, and D. Ratcliff. Objective-subjective measurement of meat tenderness. J. Texture Stud., 6, 315 (1975).

[397]J. Rasekh, A. Kramer, and R. Finch. Objective evaluation of canned tuna sensory quality. J. Food Sci., 35, 417 (1970).

[398]A. Bednarcyzk and A. Kramer. Identification and evaluation of the flavor-significant components of ginger essential oil. Chem. Senses & Flavor, 1, 377 (1975).

[399]T. Aishima and A. Nobrihara. Evaluation of soy sauce flavor by stepwise multiple regression analysis of gas chromatographic profiles. Agr. Biol. Chem., 41, 1841 (1977).

[400]W.G. Galetto and A.A. Bednarczyk. Relative flavor contribution of individual volatile components of the oil of onion. J. Food Sci., 40, 1165 (1975).

foods from instrumental measures of texture,[332] intensity of onion flavor from GC measures,[401-403] texture of fish-gels from compression tests,[404] off-odor intensity of irradiated beef fat by GLC measures,[406] and flavor scores for orange juice from a variety of physicochemical measures.[407]

Recently, Moskowitz[361,408] has extended the application of multiple regression to the prediction of overall dissimilarity between pairs of stimuli through the use of difference scores on each of a series of attributes. That is, the predictant variable is the rating of the qualitative dissimilarity of two stimuli, while the predictor variables are scores representing the difference in ratings between the two stimuli on n sensory attributes. This analysis allows the food researcher to determine which qualitative attributes of food products are most responsible for the perception of overall dissimilarity between the products. Moskowitz has coined the term "salience analysis" to describe this specific application of multiple regression techniques.

[401]T. Persson and E. von Sydow. A quality comparison of frozen and refrigerated cooked sliced beef. 2. Relationships between gas chromatographic data and flavor scores. J. Food Sci., 37, 234 (1972).

[402]T. Persson, E. von Sydow, and C. Akesson. The aroma of canned beef: Models for correlation of instrumental and sensory data. J. Food Sci., 38, 682 (1972).

[403]T. Persson and E. von Sydow. The aroma of canned beef: Application of regression models relating sensory and chemical data. J. Food Sci., 39, 537 (1974).

[404]D.D. Hamann and N.B. Webb. Sensory and instrumental evaluation of material properties of fish gels. J. of Texture Stud., 10, 117 (1979).

[405]A. Khayat. Correlation of off-odor scores of canned tuna with gas chromatographic data. J. Food Sci., 44, 37 (1979).

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[407]R.D. Carter and J.A. Cornell. Use of regression models in objective flavor evaluation of processed orange juice during four seasons. In Flavor Quality: Objective Measurement. R.A. Scanlan (ed). Washington, DC: American Chemical Society, 104 (1977).

[408]H.R. Moskowitz. Combination rules for judgments of odor quality differences. Agri. Food Chem., 22, 740 (1974).

5. Response Surface Methodology

Thus far, we have considered only first-order linear regression equations. However, second- and third-order polynomial regression equations (containing quadratic and cubic terms, respectively) are frequently required in order to afford a high degree of predictability of the dependent variable. **Response surface methodology** (RSM) consists of a number of techniques for obtaining data that will enable one to fit such equations to the data. The methodology derives its name from the fact that when the independent variables in a regression equation are allowed to vary and the dependent variable is plotted as a function of the values of these variables, a regression surface or **response surface** is defined. By examining the response surface for a set of data, it is possible to identify those combinations of levels of the independent variables that produce maxima and minima of the dependent variable. For example, if the dependent variable is a sensory response, such as the overall acceptability of the product, and the independent variables are ingredients, then the examination of the response surface would enable the manufacturer to identify that combination of levels of ingredients that produces the most acceptable product. Alternatively, response contours can be plotted that show the various combinations of levels of ingredients that all produce the same level of acceptability.

In actual practice, the major problem in establishing response surfaces is the fact that the manufacturer must obtain responses to products representing all possible combinations of ingredient levels. Response surface methodology circumvents this problem by examining only certain fixed levels of the independent variables and further reduces the number of test samples through the use of specialized experimental designs. The result of the application of these techniques is to enable manufacturers to optimize their products by predicting the combination of levels of ingredients or other variables that produce a maximum or desired level of acceptability. Furthermore, if more than one combination of ingredients will produce the same desired response, then the manufacturer can choose that combination that

minimizes total ingredient costs. Several useful applications of RSM and related techniques have appeared in the literature.[409-416]

VII. Summary

The study of the sensory components of food quality can best be thought of in terms of both the qualitative and guantitative dimensions of sensory experience.

Significant contributions to the understanding of the qualitative dimensions of taste, smell, texture, vision and audition have been made by investigators in many disciplines. Although much progress has been made in identifying basic qualitative dimensions within each sense modality, the complexity of food stimuli and the intricacies of sensory interaction often require specialized descriptive/analytic approaches in order to describe adequately the sensory properties of food. Such approaches as the Arthur D. Little Flavor Profile Method, the General Foods Texture Profile Method and Q.D.A. have filled this role in the food industry.

[409]R.G. Henika. Simple and effective system for use with response surface methodology. Cereal Science Today, 17, 309 (1972).

[410]M.R. Henselman, S.M. Donatoni, and R.G. Henika. Use of response surface methodology in the development of acceptable high protein bread. J. Food Sci., 39, 943 (1974).

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[414]H.R. Moskowitz, D.W. Stanley, and J.W. Chandler. The eclipse method: Optimizing product formulation through a consumer generated ideal sensory profile. Can. Inst. Food Sci. & Tech. J., 10, 161 (1977).

[415]J.G. Kapsalis and H.R Moskowitz. Views on relating instrumental tests to sensory assessment of food texture. Applications to product development and improvement. J. Texture Stud., 9, 371 (1978).

[416]Y.P.C. Hsieh, A.M. Pearson, and W.T. Magee. Development of a synthetic meat flavor mixture by using response surface methodology. J. Food Sci., 45, 1125 (1980).

Studies of the **quantitative** dimensions of sensory experience have focused on the measurement process itself and significant contributions have been made by psychologists, mathematicians, statisticians, food technologists and other scientists involved in problems of sensory measurement. By far, the greatest schism existing among sensory scientists in the food industry today involves the method of quantifying sensory magnitude, and the resolution of this problem does not appear imminent. The controversy begun by Fechner and intensified by Stevens is likely to continue for some time. This report has highlighted the various approaches and has provided the reader with the major advantages and disadvantages of these methods. The ultimate choice of method must be decided by the individual investigator, keeping in mind the question(s) to be answered and the resources available to answer them.

The combination of qualitative and quantitative methods of sensory analysis provides the food scientist with the basic tools for assessing the sensory quality of food. These methods, in combination with the mathematical techniques of correlation, regression and multivariate statistical analysis, enable the investigators to explore fully the relationships among sensory and objective measures of food quality. These techniques assist the food scientist in answering such questions as (1) what are the important sensory and perceptual dimensions underlying the appreciation of rations? (2) how do these attributes relate to or predict consumer acceptability of the rations? and (3) how can objective measures be related to sensory measures for the purposes of quality assurance and ration development? The judicious selection of sensory methods, as described in this report, and instrumental methods will lead to the development of better rations and assure their quality for tomorrow's soldier.

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IX. APPENDIX

Fechner's derivation of his psychophysical law began with Equation 3. Fechner's first step was to assume that differentials could be substituted for the differences (Δs) in the equation. The second step involved the integration of this function between stimulus threshold (ϕ_0) and any suprathreshold physical intensity (ϕ). This is expressed mathematically as:

$$\int_{\Psi_0}^{\Psi} d\Psi = \int_{\phi_0}^{\phi} c \, \frac{d\phi}{\phi} \tag{12}$$

or after integration,

$$\Psi = c \log \phi + C \tag{13}$$

where Ψ is the sensation magnitude, ϕ is the intensity of the stimulus, C is a constant of integration, and c is a constant of proportionality. Fechner termed Equation 13 the "measurement formula" and it is in the form as required by Equation 1. To eliminate the unknown constant of integration, Fechner assumed that the sensation magnitude experienced at threshold is zero, therefore

$$c \log \phi_0 + C = 0 \tag{14}$$

or

$$C = -c \log \phi_0. \tag{15}$$

When the value for C from Equation 15 is substituted into Equation 13, the result is

$$\Psi = c \log \phi - c \log \phi \tag{16}$$

which reduces to

$$\Psi = c \log \frac{\phi}{\phi_0}. \tag{17}$$

If the stimulus intensity at threshold is taken as the unit of stimulus measure, Equation 17 further reduces to:

$$\Psi = c \log \phi \tag{18}$$

which is the form of the equation that is most commonly known as "Fechner's Law."

Fechner's derivation of the law has been criticized on various grounds. First is the fact that Fechner assumed Weber's Law to be true. Although it has been well confirmed that Weber's Law holds in the mid-range of most stimulus dimensions, the relationship fails at very high and very low intensities. At these extremes, the difference threshold becomes larger than is predicted by Weber's Law.

The second and most important criticism of Fechner's derivation is that it is based on the assumption that all j.n.d.s are equal. This criticism is well deserved, for it is, indeed, only an assumption. There is no a priori reason for its acceptance, and the only empirical evidence which may bear on

the truth of the assumption would require some already existing measure of sensation. There is no obvious reason why Fechner did not merely assume that Weber's Law held for both physical and psychological magnitudes. This assumption would have led to a different "fundamental formula," $\Delta\phi/\phi = \Delta\Psi/\Psi$, the mathematical development of which entails a psychophysical power law.

A third criticism of Fechner lies in the validity of his integration of the fundamental formula. In order to apply the calculus to Equation 3, $\Delta\phi$ and $\Delta\Psi$ must become infinitesimal (approach $d\phi$ and $d\Psi$). Although this does not pose a problem for $d\phi$, since one can conceive of an infinitesimal change in a physical intensity, it is unclear as to what $d\Psi$, an infinitesimal change in sensation represents. By definition, $\Delta\Psi$ is the sensation difference which is just large enough to be noticeable. Any difference less than $\Delta\Psi$ would not be perceived at all.